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STUDY ON PIPELINE LEAKING DETECTION AND LOCATION BASED ON INTUITIONISTIC FUZZY SET THEORY

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Original scientific paper

From the view of time sequence, a petroleum pipeline leak detection and location method is proposed based on intuitionistic fuzzy set theory. The method uses wavelet decomposition and semi-hard-and-soft thresholding method to remove the noise of signal. Secondly, selecting fixed-length normal dynamic pressure wave signal sequences as the template sequence, and the same-length sub-sequence of acquisition signals is selected as matching sequence, the intuitionistic fuzzy sets of two sub-sequences signals corresponding to power spectrum are constructed, and their intuitionistic fuzzy similarity and entropy calculated. In the end, according to the similarity degree between normal and acquisition signals sequences, whether there is leakage of petroleum pipeline can be automatically judged. If leakage occurs, the leaking location can be determined by means of the intuitionistic fuzzy entropy difference. The experimental results show that the proposed intuitionistic fuzzy set theory for oil pipeline leak detection and location method is simple, effective and has high locating accuracy.

Keywords: *anomaly detection; dynamic pressure wave; intuitionistic fuzzy entropy; intuitionistic fuzzy similarity; pipeline leaking*

Otkrivanje i lokacija curenja cjevovoda utemeljena na intuicijskoj teoriji neizrazitih skupova

Izvorni znanstveni članak

Uzimajući u obzir vremenski slijed, predlaže se metoda za otkrivanje i lociranje curenja cjevovoda na temelju intuicijske teorije neizrazitih (fuzzy) skupova. Metoda koristi wavelet dekompoziciju i semi-hard-and-soft thresholding metodu za otklanjanje buke signala. Zatim, odabirući nizove signala vala normalnog dinamičkog tlaka nepromjenjive dužine kao šablonu za niz (sekvencu) i podsekvencu iste dužine prijemnih signala kao odgovarajući niz, tvore se intuicijski neizraziti nizovi od signala dviju podsekvenci koje odgovaraju spektru snage, te se izračunava njihova intuicijska fuzzy sličnost i entropija. Na kraju, prema stupnju sličnosti između sekvenci normalnih i prijemnih signala, automatski se procjenjuje da li postoji curenje na naftovodu. Ako postoji, mjesto curenja se može odrediti pomoću razlike u intuicijskoj fuzzy entropiji. Eksperimentalni rezultati pokazuju da je predložena intuicijska metoda neizrazitih skupova za otkrivanje i lociranje curenja naftovoda jednostavna, učinkovita i s visokom točnošću lociranja.

Ključne riječi: *curenje cjevovoda; intuicijska fuzzy entropija; intuicijska fuzzy sličnost; otkrivanje anomalije; val dinamičkog tlaka*

1 Introduction

With the rapid development of network technology, the traditional system monitoring conducted by man cannot meet the needs of the fast and sustainable development of petroleum pipeline transportation. At present, with the fast development in disciplines like instrument, automation, informatics, and communication network, petroleum pipeline leak detection and location technology has also achieved considerable progress, and various methods have emerged, such as acoustic detection, optical fibre detection, cable detection, air sampling, and negative pressure wave detection [1]. In particular, on the basis of negative pressure wave detection, the integration of some technologies, such as sensor technology, network technology, embedded technology, signal processing, pattern recognition, and intellectual information processing etc., has developed and become an important means and development direction of pipeline leak detection and location.

Among various methods of oil and gas pipeline leak detection, negative pressure wave detection possesses high sensitivity and location accuracy. When leak occurs in a pipeline, the transient negative pressure wave emerges and propagates upstream and downstream. This method uses the time difference between upstream and downstream arrivals to detect and locate the leak. In the process of fluid transportation, due to interference factors, including environment and interaction between fluid and pipeline wall and so forth, background noise will come into being, which is detrimental to signal analysis. Therefore the acquisition sensor information should first be filtered and denoised [2] before feature extraction and identification so as to accurately detect leak signals [3,4]; however, the intelligence science detection, combining feature extraction of denoised pressure wave signals and machine learning, is very time-consuming and cannot meet the needs of online leak signal detection when instantaneity is highly required. Given the fact that pressure wave signals gained by petroleum pipeline detection is typically non-stationary, many scholars have employed statistic analysis [5, 6], waveform analysis [7 ÷ 9], and image processing [10, 11] in leak detection and obtained practical achievements. In addition, pressure wave signals in petroleum pipeline can be seen as time sequences and mining the anomaly patterns [12, 13] of this sequence has become one of the important means of petroleum pipeline leak anomaly detection. In order to conduct in-depth study on pipeline leak detection, information measure, information geometry and chaotic dynamic system attract much attention and become the important hotspot issues in this field.

Environment and propagation cause certain random noise in negative pressure wave signals acquisition by pipeline sensors and negative pressure wave has complicated formation mechanism. Thus, pipeline leak detection should adopt various un-deterministic methods, such as Zadeh's fuzzy set theory, vague set theory, rough set theory, intuitionistic fuzzy set theory, and Type-2 fuzzy set theory. Scholars have also proposed expert system methods to realize pipeline leak detection [14 ÷ 16], including fuzzy rule decision-making, classification, and fuzzy comprehensive evaluation. However, this detection method involves complicated fuzzy rules; the rational selection of decision weight requires a great deal of expert knowledge and experience; the accuracy and universality of detection will face many challenges and even cannot satisfy the needs of the development of embedded online monitoring system. Therefore, in order to overcome those shortcomings, this paper makes use of the anomaly detection which combines similarity and entropy in reference [17] to explore one of the hotspot uncertain research methods—an effective pipeline leak detection and location method which integrates intuitionistic fuzzy similarity and intuitionistic fuzzy entropy. This can promote the new application of intuitionistic fuzzy set theory in pipeline leak detection and location, improve the speed, accuracy, and universality of existing Zadeh's fuzzy leak detection and location, and actively propel the intelligentialization and commercialization of oil pipeline leak detection system.

The proposed method adopts wavelet decomposition and semi-hard-and-soft thresholding method to remove the noise, uses Fourier transform to conduct power spectrum analysis on pressure wave signal [18, 19], and integrates intuitionistic fuzzy similarity with intuitionistic fuzzy entropy to detect and locate leaking. This method does not need to set intuitionistic fuzzy decision-making rules and threshold value parameters. It is easy to realize, runs fast and consumes little storage. Thus it can fulfil the needs of the development of embedded online monitoring system.

2 The principle of negative pressure wave leak detection and location

When leak occurs in a pipeline, due to the pressure difference inside and outside the pipeline, the fluid near the leaking point leaves rapidly and the pressure drops sharply. The fluid near the leaking point goes to the leaking point due to the pressure difference. This process propagates upstream and downstream, causing the pressure wave with certain speed at the leaking point.

Assume that the tested pipeline is *L* (m); fluid velocity is *v* (m/s); negative pressure wave's velocity is *a* (m/s). When leak occurs at *X* (m) from the pipeline front end, the time when the negative pressure wave runs from the leaking point to the pipeline front end is t_1, and the time when the wave arrives at the back end is t_2. Let $\Delta t = t_1 - t_2$, and the relation can be developed as follows

$$\Delta t = \frac{X}{a-v} - \frac{L-X}{a+v}, \tag{1}$$

where *a* usually exceeds 340 m/s and *v* is between 1,5 m/s and 3 m/s. Therefore, *v* can be ignored. Then

$$X = \frac{L + a\Delta t}{2}. \tag{2}$$

In Eq. (2), *X* is the distance between the leaking point and pressure measurement point at the front end of pipeline (m); *L* is the length of tested pipeline (m); *a* is the propagation velocity of pressure wave (m/s); Δ*t* is the time difference between the front and back end sensors detecting negative pressure wave (s). Among these variables, *L* can be directly measured while *a* and Δ*t* are to be calculated.

In addition, for the problems in the present pressure wave pipeline leak detection, references [2, 20, 21] propose various ways to improve negative pressure wave technology and to enhance the reliability and accuracy of pipeline leak detection.

3 Dynamic pressure wave signal denoising

When the pipeline is in operation, due to various interference factors at the scene, signals collected at the two ends of the pipeline will mix with a large amount of random noise. These noise signals make it more difficult to extract real pressure wave signals. To address this problem, this paper proposes to use wavelet domain and semi-hard-and-soft threshold to denoise dynamic pressure wave signals and to achieve real pressure wave signals.

Since signals and noise show different levels of sparsity in wavelet domain when scale changes, using traditional soft and hard thresholding method to denoise cannot remove the mixed noise effectively. So semi-hard threshold function [22] is combined with improved soft threshold and extended as the semi-hard-and-soft threshold function, as follows

$$\hat{w}_{j,k} = \begin{cases} w_{j,k} - \alpha\lambda f(w_{j,k}, \lambda, \alpha), \ \left|w_{j,k}\right| \geq a \\ 0, \ \left|w_{j,k}\right| < b \\ \mathrm{a}(\mathrm{a} - b)^{-1}(w_{j,k} - b), \ \mathrm{b} \leq \left|w_{j,k}\right| < a \end{cases}, \tag{3}$$

where $f(w_{j,k}, \lambda, \alpha) = 2 - (1 + \exp(\lambda^{-1} \times (-\left|w_{j,k}\right| + \alpha)))^{-1}$, λ is threshold value and $\lambda = \sigma\sqrt{2 \cdot \ln N}$, where σ is mean square deviation of noise and *N* is sampling duration. Usually, precise mean square deviation of noise cannot be obtained and it can be estimated as $\sigma = MAD(|cD_1|)/0{,}6745$, where *MAD* represents mean absolute deviation. The high-frequency coefficient cD_1 obtained through first-level decomposition is used to estimate noise's mean square deviation. In the meantime, set $a = 3\lambda$, $b = (0{,}5 \sim 1{,}5)\lambda$ and $0 \leq \alpha \leq 1$.

The semi-hard-and-soft threshold function is not only continuous in wavelet domain but also possesses the characteristic of high-order derivative function when $|w_{j,k}| \geq a$. Inspect the function

$$\hat{w}_{j,k} = w_{j,k} - \alpha\lambda(2 - (1 + \exp(\lambda^{-1} \times (-\left|w_{j,k}\right| + \alpha)))^{-1}. \tag{4}$$

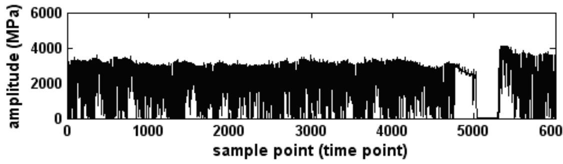
The basic idea of this function is that because the absolute value of wavelet coefficient $\hat{w}_{j,k}$, estimated through soft thresholding method, is λ less than $w_{j,k}$, reconstruction accuracy is affected and this deviation needs to be reduced. But in hard threshold method, reducing the deviation to zero is not the optimal solution since $w_{j,k}$ is composed of $u_{j,k}$ and $v_{j,k}$ and the impact of $v_{j,k}$ causes $w_{j,k} \neq u_{j,k}$. Therefore, setting $|w_{j,k} - \lambda| < \hat{w}_{j,k} \leq w_{j,k}$ will make the estimated wavelet coefficient $\hat{w}_{j,k}$ more close to $w_{j,k}$.

For parameter α, there exist three scenarios: (1) when $\alpha = 0$, threshold function (3) equals semi-hard threshold denoising function; (2) when $\alpha = 1$, threshold function (3) degrades into a soft thresholding denoising function; (3) when $0 < \alpha < 1$ and $w_{i,j} \to \pm \infty$, $|\hat{w}_{j,k} - w_{j,k}| \to \alpha\lambda$. Therefore, this function can reduce the constant deviation in soft threshold method, enhance reconstruction accuracy, and improve denoising effects.

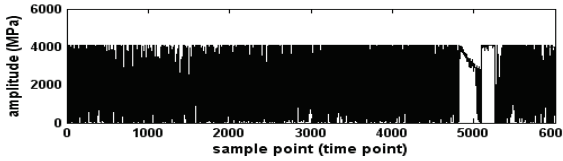
Compared with soft and hard threshold functions, the new threshold function (4) provides better and more flexible choice. As long as λ is appropriately adjusted between 0 and 1, better denoising effects can be achieved.

The basic idea of using new wavelet threshold function to denoise is to continuously perform many wavelet analyses on dynamic pressure wave signals, obtain high-frequency wavelet coefficients at different levels, then conduct threshold value compression through threshold function (4), remove noise, and use the processed wavelet coefficients to reconstruct valid real signals through inverse wavelet transform.

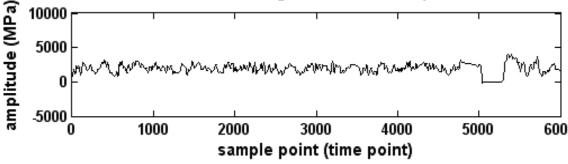
At some given time period, when leak occurs in a petroleum pipeline, the original pressure wave acquisition signals are collected by the upstream and downstream front and back sensors and the denoising results are presented in Fig. 1.



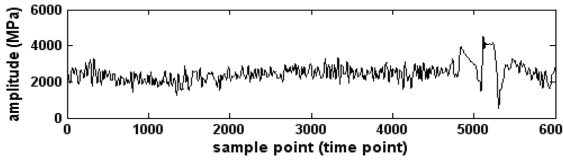
(a) upstream pressure wave signals



(b) downstream pressure wave signals



(c) the denoised upstream signals



(d) the denoised downstream signals

Figure 1 the upstream and downstream pressure wave signals of oil pipeline

4 Pipeline leak detection and location based on intuitionistic fuzzy set theory

Because the traditional Zadeh's fuzzy set description, adopted in pressure wave signal analysis, can only express the affirmative to signals, the unknown features of pressure wave signals cannot be described and the fuzzy rule base lacks completeness, which can lead to false detection and missing detection of leak signals. Aiming at these problems, this paper proposes new method for petroleum pipeline leak detection and location which combines intuitionistic fuzzy similarity and intuitionistic fuzzy entropy in intuitionistic fuzzy set theory.

4.1 Basic theory of intuitionostic fuzzy sets

Since American scholar Zadeh established fuzzy sets in 1 965, the research and application of traditional fuzzy set theory have achieved great progress. But Zadeh's fuzzy sets only include affirmative membership of fuzzy concepts while in practical application, affirmation and negation often emerge and also between the two lies the unknown indeterminacy. Thus, the limitation of applying Zadeh's fuzzy set theory to practical problem-solving is gradually exposed and attracts great attention from scholars.

Definition 1 Let X be a nonempty finite set, then $F = \{< x, \mu_F(x) > | x \in X\}$ is a fuzzy set, where μ_F is the membership function of fuzzy set F, and $\mu_F(x): X \to [0,1]$, $\mu_F(x)$ denotes the degree of membership of the element $x \in X$ to the fuzzy set F.

Atanassov generalized Zadeh's fuzzy sets, and provided the concept of intuitionistic fuzzy sets [23].

Definition 2 Let X be a nonempty finite set, $A = \{< x, \mu_A(x), \nu_A(x) > | x \in X\}$ is an intuitionistic fuzzy set, where $\mu_A(x)$ and $\nu_A(x)$ are the degree of membership and non-membership of the element $x \in X$ to the set A, namely

$$\mu_A(x): X \to [0,1], x \in X \to \mu_A(x) \in [0,1],$$
$$\nu_A(x): X \to [0,1], x \in X \to \nu_A(x) \in [0,1],$$

and the constraint conditions should be satisfied, $0 \le \mu_A(x) + \nu_A(x) \le 1, x \in X$. In addition, let $\pi_A(x) = 1 - \mu_A(x) - \nu_A(x), \forall x \in X$, and this denotes the hesitation margin or unknown degree of $x \in X$ to A. $\pi_A(x)$ is the intuition fuzzy index of $x \in X$ to A and $0 \le \pi_A(x) \le 1, x \in X$. In particular, if $\pi_A(x) = 0$, $x \in X$, then A degrades into traditional Zadeh's fuzzy set. Thus, Zadeh's fuzzy set is a special case in intuitionistic fuzzy sets.

In addition, the intersection and union of any two intuition fuzzy sets A, B can be defined as

$$\begin{aligned} A \cap B &= \{< x, \mu_{A \cap B}(x), \ \nu_{A \cup B}(x) > | x \in X\}, \\ A \cup B &= \{< x, \mu_{A \cup B}(x), \ \nu_{A \cap B}(x) > | x \in X\}, \end{aligned} \tag{5}$$

where

$$\mu_{A \cap B}(x) = \min \ \{\mu_A(x), \ \mu_B(x)\},$$
$$\mu_{A \cup B}(x) = \max \ \{\mu_A(x), \ \mu_B(x)\},$$
$$\nu_{A \cap B}(x) = \max \ \{\nu_A(x), \ \nu_B(x)\},$$
$$\nu_{A \cup B}(x) = \min \ \{\nu_A(x), \ \nu_B(x)\}.$$

For the intuition fuzzy set in nonempty finite set *X*, $A=\{<x,\mu_A(x),\nu_A(x)>|\,x\in X\}$, and its standard Zadeh's complementary set is $A^c=\{<x,\nu_A(x),\mu_A(x)>|\,x\in X\}$.

The traditional fuzzy entropy can be used to describe the uncertain degree of Zadeh's fuzzy sets and many achievements have been obtained. Later, reference [24] puts forward the fuzzy entropy concept of intuitionistic fuzzy sets which is to describe the uncertain degree of intuitionistic fuzzy sets but its definition only includes the unknown uncertain degree of intuitionistic fuzzy sets and has some defects. So reference [25] proposes new axiomatic definition of intuitionistic fuzzy sets to depict the fuzzy and unknown uncertain of intuitionistic fuzzy sets, which receives great attention from scholars.

The axiomatic definition of fuzzy entropy of traditional fuzzy sets can be described as

Definition 3 Function $E: IFS(X)\rightarrow[0,1]$ is the fuzzy entropy of intuitionistic fuzzy sets (*IFS*(*X*) is the set of all intuitionistic fuzzy sets in the domain of discourse *X*). If the following conditions can be met [25]:

(1) $E(A)=0$, if and only if *A* is not a fuzzy set;

(2) $E(A)=1$, if and only if $\forall x\in X$, then $\mu_A(x)=\nu_A(x)$;

(3) The intuitionistic fuzzy entropy of intuitionistic fuzzy set *A* equals that of its complementary set A^c, namely $E(A)=E(A^{c^*})$;

(4) when $\mu_B(x)\le\nu_B(x)$, if $\mu_A(x)\le\mu_B(x)$ and $\nu_A(x)\ge\nu_B(x)$; or when $\mu_B(x)\ge\nu_B(x)$, if $\mu_A(x)\ge\mu_B(x)$ and $\nu_A(x)\le\nu_B(x)$, then $E(A)\le E(B)$.

The fourth condition of this axiomatic definition of intuitionistic fuzzy entropy requires that every element should correspond with some sequence. This strict condition greatly restricts the application scope of this entropy. For example, the intuitionistic fuzzy sets $A=\{<x,\ 0{,}1,\ 0{,}3>|\,x\in X\}$, $B=\{<x,\ 0{,}4,\ 0{,}5>|\,x\in X\}$ cannot be compared for they cannot meet the fourth condition. Aimed at the defects of the axiomatic definition of intuitionistic fuzzy entropy, reference [26] proposes the improved axiomatic definition of intuitionistic fuzzy entropy as follows

Definition 4 Function $E: IFS(X)\rightarrow[0,1]$ is the fuzzy entropy of intuitionistic fuzzy sets. If the following conditions can be met:

(1) $E(A)=0$, if and only if *A* is not a fuzzy set;

(2) $E(A)=1$, if and only if $\forall x\in X$, then $\mu_A(x)=\nu_A(x)$;

(3) The intuitionistic fuzzy entropy of intuitionistic fuzzy set *A* equals that of its complementary set A^c, namely $E(A)=E(A^{c^*})$;

(4) The fuzzy entropy of intuitionistic fuzzy set *A* is the decreasing function of the deviation between membership function and non-membership function and the increasing function of $\pi_A(x)$.

The expression for intuitionistic fuzzy entropy corresponding to the axiomatic definition is [24, 26, 27]

$$E_1(A)=\frac{1}{|X|}\sum_x\frac{\min\{\mu_A(x),\nu_A(x)\}+\pi_A(x)}{\max\{\mu_A(x),\nu_A(x)\}+\pi_A(x)} \tag{6}$$

$$E_2(A)=\frac{1}{|X|}\sum_x\cos\left(\frac{\mu_A(x)-\nu_A(x)}{2(1+\pi_A(x))}\pi\right), \tag{7}$$

$$\begin{aligned}E_3(A)=&-\frac{1}{|X|\ln 2}\sum_x\left(f(\mu_A(x))+f(\nu_A(x))\right)+\\&+\frac{1}{|X|\ln 2}\sum_x\left(f(1-\pi_A(x))+\pi_A(x)\ln 2\right),\end{aligned} \tag{8}$$

where $f(x)=x\ln x$.

The intuitionistic fuzzy similarity is used to describe the level of similarity between two intuitionistic fuzzy sets. The axiomatic definition of intuitionistic fuzzy similarity of intuitionistic fuzzy sets can be described as

Definition 5 Function $S: IFS(X)\times IFS(X)\rightarrow[0,1]$ denotes the intuitionistic fuzzy similarity of intuitionistic fuzzy sets ($IFS(X)$ is the set of all intuitionistic fuzzy sets in the domain of discourse *X*). If the following conditions can be met [28]:

(1) For any two intuitionistic fuzzy sets *A* and *B*, then $S(A,B)=S(B,A)$;

(2) For any non-fuzzy set *D* and its complementary set D^c, then $S(D,D^c)=0$;

(3) For any intuitionistic fuzzy set *C*, then $S(C,C)=\max\limits_{A,B\in IFS(X)}S(A,B)$;

(4) For any intuitionistic fuzzy set *A*, *B*, and *C*, if $A\subset B\subset C$, and then $S(A,B)\ge S(A,C)$ and $S(B,C)\ge S(A,C)$.

The widely-used fuzzy similarity formulas are

$$S_1(A,B)=\frac{\sum\limits_{x\in X}f_1(\mu_A(x),\nu_A(x),\mu_B(x),\nu_B(x))}{\sum\limits_{x\in X}f_2(\mu_A(x),\nu_A(x),\mu_B(x),\nu_B(x))}, \tag{9}$$

where

$$\begin{aligned}&f_1(\mu_A(x),\nu_A(x),\mu_B(x),\nu_B(x))=\min\{\mu_A(x),\mu_B(x)\}+\\&+\min\{\nu_A(x),\nu_B(x)\}+2\min\{\pi_A(x),\pi_B(x)\},\\&f_2(\mu_A(x),\nu_A(x),\mu_B(x),\nu_B(x))=\max\{\mu_A(x),\mu_B(x)\}+\\&+\max\{\nu_A(x),\nu_B(x)\}+2\max\{\pi_A(x),\pi_B(x)\}.\end{aligned}$$

$$s_2(A,B)=\frac{\sum\limits_{x\in X}g_1(\mu_A(x),\nu_A(x),\mu_B(x),\nu_B(x))}{\sum\limits_{x\in X}g_2(\mu_A(x),\nu_A(x),\mu_B(x),\nu_B(x))}, \tag{10}$$

where

$$\begin{aligned}&g_1(\mu_A(x),\nu_A(x),\mu_B(x),\nu_B(x))=\\&=2\,\mu_A(x)\mu_B(x)+2\nu_A(x)\nu_B(x)+2\min\{\pi_A(x),\pi_B(x)\},\\&g_2(\mu_A(x),\nu_A(x),\mu_B(x),\nu_B(x))=\\&=\mu_A^2(x)\mu_B^2(x)+\nu_A^2(x)\nu_B^2(x)+2\max\{\pi_A(x),\pi_B(x)\}.\end{aligned}$$

In addition, certain induction relation exists between intuitionistic fuzzy entropy and intuitionistic similarity, namely $e(A)=s(A\cap A^c,A\cup A^c)$.

4.2 Leak detection based on intuitionistic fuzzy similarity

Assume that the pressure wave acquisition signals collected by the upstream and downstream sensors in petroleum pipeline are $x_i^0(l)(i=1,2;l=1,2,\cdots,N)$ (N is the sampling node 6000; signal sampling interval is 20 ms; sampling frequency is 50 Hz; and the total sampling duration is 2 minutes). Semi-hard-and-soft threshold function proposed in this paper is employed to realize wavelet multilevel decomposition and denoising, $x_i(l)(i=1,2;l=1,2,\cdots,N)$. In order to detect the anomaly in pressure wave signals, assume that when no leak occurs in the pipeline, the sub-sequence of collected and denoised upstream and downstream pressure wave signals with the length of N_1 is $r_i(l)(i=1,2;l=1,2,\cdots,N_1)$ and take it as the template sequence, where N_1 = 50 in this paper.

First, two template sequences of normal signals with the length of N_1 are $r_i(l)(i=1,2;l=1,2,\cdots,N_1)$, and their Fourier transform signal power spectrum [26-28] is calculated as $pr_i(l)(i = 1, 2; l = 1, 2, L, N_1)$ and their Atanassov's intuitionistic fuzzy set is constructed as

$$\tilde{R}_i=\left\{< l,\mu_{\tilde{R}_i}(l),v_{\tilde{R}_i}(l)>| l=1,2,\cdots,N_1\right\},i=1,2 \tag{11}$$

where

$$\mu_{\tilde{R}_i}(l)=(1+0,5(pr_i(l)-\overline{pr_i})^2)^{-2},$$
$$v_{\tilde{R}_i}(l)=1-(1+0,5(pr_i(l)-\overline{pr_i})^2)^{-0,5},$$
$$\overline{pr_i}=\frac{1}{N_1}\sum_{l=1}^{N_1}pr_i(l).$$

Then, the sequence of denoised pressure wave signals acquistion at the scene is $x_i(l)(i = 1, 2; l = 1, 2,\ldots, N)$, and the sub-sequence with the length of N_1 is selected, $x_{i,j}(l)(i = 1, 2; j = 1, 2, L, N - N_1; l = 1, 2, L, N_1)$, where $x_{i,j}(l) = x_i(j + l - 1)$. Its signal sub-sequence power spectrum is calculated as $px_{i,j}(l)(i = 1, 2; j = 1, 2, L, N - N_1; l = 1, 2, L, N_1)$ and its Atanassov's fuzzy set is constructed as

$$\widetilde{X}_{i,j}=\{< l,\mu_{\widetilde{X}_{i,j}}(l),\mu_{\widetilde{X}_{i,j}}(l)>| l=1,2,...,N_1\},$$
$$i=1,2;j=1,2,L,N-N_1. \tag{12}$$

where

$$\mu_{\tilde{X}_{i,j}}(l)=(1+0,5(px_{i,j}(l)-\overline{px}_{i,j})^2)^{-2},$$
$$v_{\tilde{X}_{i,j}}(l)=1-(1+0,5(px_{i,j}(l)-\overline{px}_{i,j})^2)^{-0,5}$$
$$\overline{px}_{i,j}=\frac{1}{N_1}\sum_{l=1}^{N_1}px_{i,j}(l).$$

At last, the intuitionistic fuzzy similarity sequence between Atanassov's intuitionistic fuzzy set $\widetilde{R}_i(i = 1, 2)$ and Atanassov's intuitionistic fuzzy set sequence $\widetilde{X}_{i,j}(i=1,2;j=1,2,L,N-N_1)$ is calculated as $S_i(j)$ = $S(\widetilde{R}_i,\widetilde{X}_{i,j})(i=1,2;j=1,2,L,N-N_1)$.

When $S_i(j)\approx 1\ (i=1,2;j=1,2,L,N-N_1)$, no oil leak happens in the petroleum pipeline during this time period; otherwise, oil leak happens in the petroleum pipeline during this time period.

4.3 Leak location based on intuitionistic fuzzy entropy

If the similarity theory of intuitionistic fuzzy sets detects the anomaly in dynamic pressure wave signals, then leak happens in the petroleum pipeline, and intuitionistic fuzzy entropy in intuitionistic fuzzy set theory is employed to locate the leaking point. The detailed steps are as follows:

First, the two template sequences of normal signals with the length of N_1 are $r_i(l)(i=1,2;l=1,2,\cdots,N_1)$, and their Fourier transform signal power spectrum is calculated as $pr_i(l)(i = 1, 2; l = 1, 2, L, N_1)$ and normalized as

$$pr_i^*(l)=\frac{pr_i(l)-\min\limits_{1\le l\le N_1}\{pr_i(l)\}}{\max\limits_{1\le l\le N_1}\{pr_i(l)\}-\min\limits_{1\le l\le N_1}\{pr_i(l)\}},$$
$$i=1,2;l=1,2,\cdots,N_1 \tag{13}$$

And their Atanassov's intuitionistic fuzzy set is constructed as

$$\tilde{R}_i^*=\left\{< l,\mu_{\tilde{R}_i^*}(l),v_{\tilde{R}_i^*}(l)>| l=1,2,\cdots,N_1\right\},i=1,2 \tag{14}$$

where

$$\mu_{\tilde{R}_i^*}(l)=(1+0,5(pr_i^*(l)-\overline{pr_i}^*)^2)^{-2},$$
$$v_{\tilde{R}_i^*}(l)=1-(1+0,5(pr_i^*(l)-\overline{pr_i}^*)^2)^{-0,5},$$
$$\overline{pr_i}^*=\frac{1}{N_1}\sum_{l=1}^{N_1}pr_i^*(l).$$

Then, the sequence of denoised pressure wave signals acquisition at the scene is $x_i(l)(i = 1, 2; l = 1, 2,\ldots, N)$, and select the sub-sequence with the length of N_1, $x_{i,j}(l)(i = 1, 2; j = 1, 2, L, N - N_1; l = 1, 2, ..., N_1)$, where $x_{i,j}(l) = x_i(j + l - 1)$. Its signal sub-sequence power spectrum is calculated as $px_{i,j}(l)(i = 1, 2; j = 1, 2, ..., N - N_1; l = 1, 2, ..., N_1)$ and normalized as

$$px_{i,j}^*(l)=\frac{px_{i,j}(l)-\min\limits_{1\le l\le N_1}\{px_{i,j}(l)\}}{\max\limits_{1\le l\le N_1}\{px_{i.j}(l)\}-\min\limits_{1\le l\le N_1}\{px_{i,j}(l)\}},$$
$$i=1,2;j=1,2,\cdots,N-N_1;l=1,2,\cdots,N_1 \tag{15}$$

and its Atanassov's fuzzy set is constructed as

$$\tilde{X}_{i,j}^*=\left\{< l,\mu_{\tilde{X}_{i,j}^*}(l),v_{\tilde{X}_{i,j}^*}(l)>| l=1,2,\cdots,N_1\right\}, \tag{16}$$

$i = 1, 2; l = 1, 2, ..., N_1$

where

$$\mu_{\tilde{X}_{i,j}^*}(l) = (1 + 0{,}5(px_{i,j}^*(l) - \overline{px}_{i,j}^*)^2)^{-2},$$

$$v_{\tilde{X}_{i,j}^*}(l) = 1 - (1 + 0{,}5(px_{i,j}^*(l) - \overline{px}_{i,j}^*)^2)^{-0{,}5},$$

$$\overline{px}_{i,j}^* = \frac{1}{N_1}\sum_{l=1}^{N_1} px_{i,j}^*(l).$$

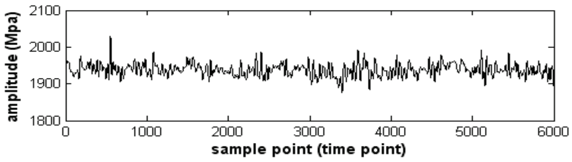
At last, the intuitionistic fuzzy entropy deviation sequence between Atanassov's intuitionistic fuzzy set $\tilde{R}_i^*$ (i = 1, 2) and intuitionistic fuzzy set sequence $\tilde{X}_{i,j}^*(i = 1, 2; j = 1, 2, L, N - N_1)$ is calculated as $VE_i(j) = | E(\tilde{R}_i^*) - E(\tilde{X}_{i,j}^*) |$ Based on the criterion $j_i^* = \max_{1 \le j \le N - N_1}\{VE_i(j)\}$, the upstream and downstream sampling nodes' time of j_1^* and j_2^* is determined as t_1 and t_2. Calculate $\Delta t = |t_1 - t_2|$ and obtain the distance between the pipeline leaking point and front end as $X = 0{,}5(L + a\Delta t)$, where a is 1000 m/s.

5 Test results and analysis

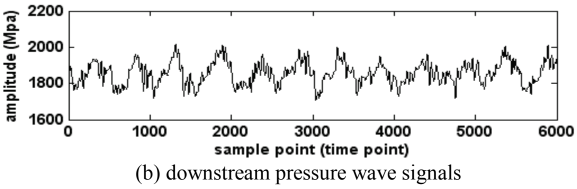
This paper proposes the intuitionistic fuzzy set theory to detect and locate petroleum pipeline leak and the test includes three parts: (1) the feasibility and effectiveness of this method; (2) its reliability and robustness; (3) and its location accuracy.

5.1 The feasibility and effectiveness of leak detection and location method

When no leak occurs in the pipeline, the denoised result of the sequence of pressure wave acquisition signals collected by the upstream and downstream sensors in the pipeline is shown in Fig. 2.



(a) upstream pressure wave signals

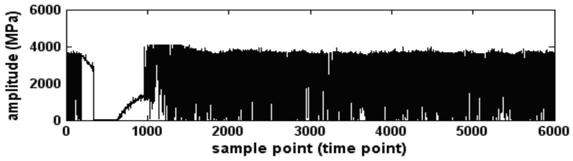


(b) downstream pressure wave signals

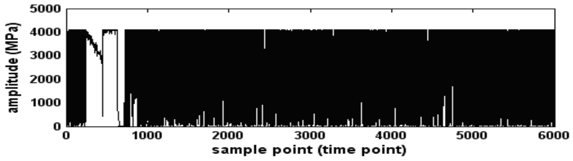
Figure 2 pressure wave signals of zero leakage oil pipeline

Select the sub-sequence with the length of N_1 as the template sequence and record as $r_i(l)(i = 1,2; l = 1,2,\cdots,N_1)$. Use autocorrelation function and Fourier transform to calculate its signal power spectrum as $pr_i(l)(i = 1, 2; l = 1, 2, \cdots, N_1)$. Fig. 3 reveals the dynamic pressure wave acquisition signals collected at the front and back end of the pipeline at the scene and its wavelet threshold denoising result.

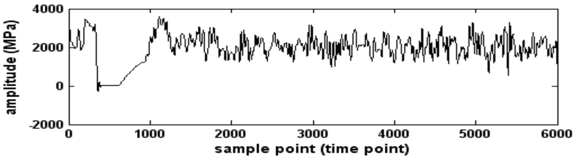
According to pressure wave acquisition signals collected when leak occurs in the pipeline in Fig. 3, the anomaly in upstream signals happens roughly between sampling node 244 and 799 while the anomaly in downstream signals happens roughly between sampling node 436 and 734. Fig. 4 shows the similarity curve achieved through template matching on the basis of intuitionistic fuzzy similarity.



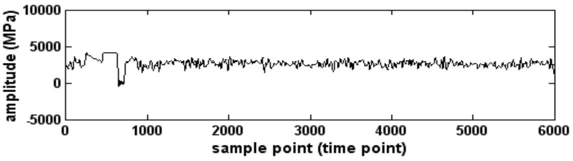
(a) upstream pressure wave signals



(b) downstream pressure wave signals

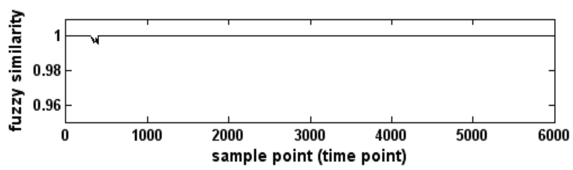


(c) the denoised results of upstream pressure wave signals

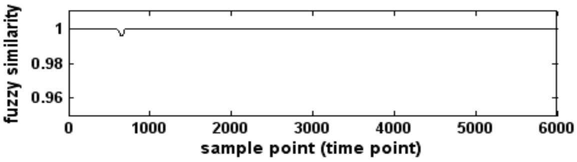


(d) the denoised results of downstream pressure wave signals

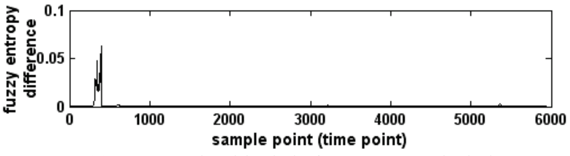
Figure 3 pressure wave signals of leaking oil pipeline



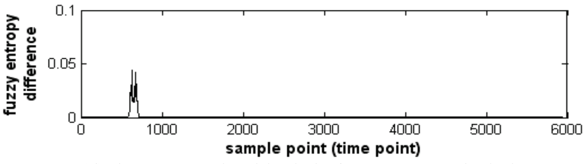
(a) upstream matched curve



(b) downstream matched curve



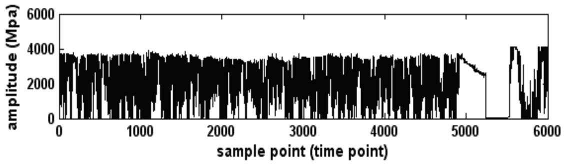
(c) upstream intuitionistic fuzzy entropy deviation



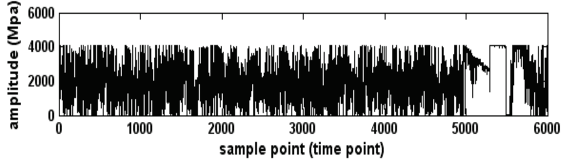
(d) downstream intuitionistic fuzzy entropy deviation

Figure 4 The detected and located results of intuitionistic fuzzy sets theory

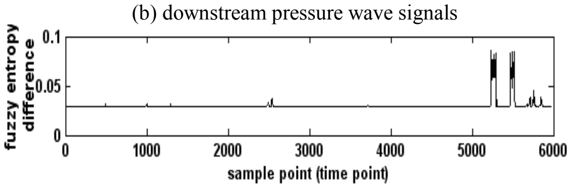
Seen from the matching curves in Fig. 4(a) and Fig. 4(b), according to the matching results of pressure wave signals at the upstream and downstream, the matching value at the upstream is less than 1,0 while the matching value at the downstream is basically close to 1,0. This indicates that oil leak occurs in this pipeline. Then intuitionistic fuzzy entropy deviation is used to locate the leakage and the result is presented in Fig. 4(c) and Fig. 4(d). The maximum deviation of front end pressure wave signals, detected through intuitionistic fuzzy entropy deviation method, occurs at sampling node 393 while the deviation value is not zero between sampling node 291 and 410; and the maximum deviation of downstream pressure wave signals, detected through intuitionistic fuzzy entropy deviation method, occurs at sampling node 679 while the deviation value is not zero between sampling node 586 and 720. After comparing the anomaly location detected through intuitionistic fuzzy entropy deviation method and the practical sampling node scope of pressure wave signals' anomaly, it can be found that the suggested intuitionistic fuzzy entropy deviation method is effective.



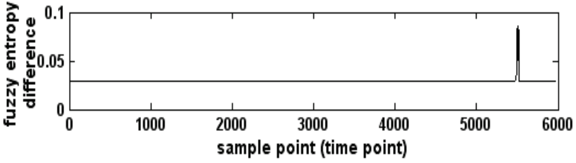
(a) upstream pressure wave signals



(b) downstream pressure wave signals



(c) upstream intuitionistic fuzzy entropy deviation



(d) downstream intuitionistic fuzzy entropy deviation

Figure 5 Pressure wave of leaking oil pipeline and its location

In order to further prove the practicability of this method, another case is depicted as follows. When leak happens in a petroleum pipeline, the pressure wave acquisition signals at the upstream and downstream of the pipeline are described in Fig. 5(a) and Fig. 5(b). The anomaly in upstream signals roughly happens between sampling node 4 900 and 5 800 while the anomaly in downstream signals occurs roughly between sampling node 5 000 and 5 900. Use the intuitionistic fuzzy similarity matching method to detect anomaly in pressure wave signals and then intuitionistic fuzzy entropy deviation method to locate the leakage. The result is shown in Fig. 5(c) and Fig. 5(d). The maximum deviation of the upstream and downstream pressure wave signals, detected through intuitionistic fuzzy entropy deviation method, occurs at sampling node 5 445 while the difference value is not zero between sampling node 5 203 and 5 290 and between 5 440 and 5 325; and the maximum deviation of the downstream pressure wave signals, detected through intuitionistic fuzzy entropy deviation method, occurs at sampling node 5 516 while the intuitionistic fuzzy entropy deviation value is not zero between sampling node 5 441 and 5 576. After comparing the anomaly location detected through intuitionistic fuzzy entropy difference and the practical sampling node scope of pressure wave signals' anomaly, it can be found that the suggested intuitionistic fuzzy entropy deviation method is feasible.

5.2 The reliability and robustness of this method

In the intuitionistic fuzzy detection and location method suggested in this paper, in order to study the impact of the differences in the selection of normal pressure wave signals on the location, take the pressure wave acquisition signals at the front and back end when leak happens in the pipeline as an example to discuss the influence of different template sub-sequences of normal pressure wave signals on detection and location.

Table 1 The location result of various length pressure wave signal templates

	Leak point in Fig. 3		Leak point in Fig. 4	
N_1	upstream	downstream	upstream	downstream
10	398	691	5 512	5 520
20	353	705	5 237	5 508
30	394	701	5 287	5 485
40	387	660	5 377	5 518
50	393	627	5 287	5 516
60	392	656	5 287	5 514
70	392	630	5 280	5 511
80	385	623	5 280	5 507
90	384	635	5 430	5 507
100	385	651	5 420	5 481
110	385	648	5 411	5 478
120	345	648	5 401	5 475
130	365	647	5 392	5 471
140	389	645	5 382	5 505
150	357	645	5 372	5 505
160	364	645	5 362	5 504
170	364	644	5 260	5 504
180	364	644	5 257	5 504
190	363	644	5 260	5 504
200	363	644	5 259	5 505

Fig. 2 exhibits normal pressure wave signals. Select any 100 sub-sequences with the length of N_1 where N_1 is 50, as matching template sequences and then apply them in the detection and location analysis of pressure wave signals at the front and back end when leak occurs in Fig. 3. Through many tests, it can be found that the selection of normal non-leakage template sub-sequences has no impact on the accuracy of detection and location of pressure wave signals at the upstream and downstream in leaking events. In addition, this paper also chooses normal pressure wave signals of no leakage at different time periods as matching template sub-sequences and achieves almost the same testing result. Thus, the selection of template sub-sequence of normal pressure wave signals at fixed time period has no influence on leak detection and location.

In order to study the effect of the length of template sub-sequences of normal pressure wave signals on leak detection and location, select template sub-sequences of upstream and downtream normal pressure wave signals with various lengths when no leak occurs in petroleum pipeline. Then conduct detection and location tests on dynamic pressure wave signals when pipeline leaks at two time periods shown in Fig. 4 and Fig. 5. The detailed results are presented in Tab. 1.

Seen from the test results in Tab. 1, the length of template sub-sequences of normal pressure wave signals exerts certain impact on intuitionistic fuzzy detection and location. Many test results have proved that if the length of template sub-sequence N_1 is greater than 150, the results of intuitionistic fuzzy detection and location are basically stable. In addition, whether the length of template sub-sequence N_1 is less than or equal to 50 or greater than 150, the best locations for intuitionistic fuzzy detection and location belong to the sampling node set when leakage signals occur. Generally speaking, in order to guarantee the accuracy and reliability of detection and location, the length of template sub-sequence N_1 can be typical values between 50 and 90, such as 50, 60, 70, and 80. This can avoid the shortcoming that time expenditure is too large due to the too long sub-sequence. In addition, normal pressure wave signals can be seen as nonlinear time sequences. The optimal theoretical value of normal pressure wave signal template sub-sequence is the minimum embedded dimension, which can be determined through correlation dimension, mutual information, and Chao algorithm etc. But this does not meet the needs of embedded online monitoring system and the discussion is omitted due to the limited space.

5.3 The accuracy of intuitionistic fuzzy entropy location

Seen from the wavy curves of pressure wave signals in Fig. 3, when anomaly starts in the front end pressure wave signals, the corresponding sampling node is 244 and when it ends, the node is 799; and when anomaly starts in the back end pressure wave signals, the corresponding sampling node is 436 and when it ends, the node is 734. Subtract the sampling nodes corresponding to the time when anomaly starts in the front and back end pressure wave signals, then multiply the result by sampling time interval 2ms and obtain the time difference $\Delta t_1 = 0{,}002 \times |244 - 436| = 0{,}384$ s. The actual value of distance between pipeline leaking point and the front pressure wave signal sensor is $X_1 = 0{,}5(L + a\Delta t_1) = 0{,}5L + 65{,}28$ m. If the length of the matching template sub-sequence N is 50, use intuitionistic fuzzy entropy location method to determine that the sampling node of anomaly in the front end pressure wave signals is 393, and the sampling node of anomaly in the back end pressure wave signals is 627, so the time difference is $\Delta t_2 = 0{,}0002 \times |393 - 627| = 0{,}468$ s, and the distance between the located leaking point and the front pressure wave signal sensor is $X_2 = 0{,}5(L + a\Delta t_2) = 0{,}5L + 79{,}56$ m. Thus, leaking location error gained through intuitionistic fuzzy entropy location method is 14,28 m. If the template sub-sequences with the typical lengths of 50, 60, 70, 80, and 90 are selected, the maximum error of intuitionistic fuzzy entropy leak location (the location results are shown in Table 1) of dynamic pressure wave signals in Fig. 3 is 20,06 m, while the minimum is 14,28 m. If the template sequence is 200 long, its intuitionistic fuzzy entropy leak detection error is 61,54 m. Assume that the distance between the upstream and downstream sensors in pipeline L is 30 000 m and select template sequence of typical lengths. The maximum of corresponding relative error is 0,67 ‰, while the minimum is 0,48 ‰.

Similarly, seen from the wavy curves of pressure wave signals in Fig. 4, the actual value of distance between pipeline leaking point and the upstream pressure wave signal sensor is $0{,}5L + 34$ m. If the length of the matching template sub-sequence N is 50, use intuitionistic fuzzy entropy location method to detect the distance between pipeline leaking point and the upstream pressure wave signal sensor as $0{,}5L + 77{,}86$ m, and then the error of intuitionistic fuzzy entropy location is 33,86 m. If the template sub-sequences with the typical lengths of 50, 60, 70, 80, and 90 are selected, the maximum error of intuitionistic fuzzy entropy leak location (the location results are shown in Tab. 1) of dynamic pressure wave signals in Fig. 4 is 44,54 m while the minimum is 7,82 m. If the template sequence has 200 points, its intuitionistic fuzzy entropy leak detection error is 49,64 m. Assume that the distance between the upstream and downstream sensors in pipeline L is 30 000 m and select template sequence of typical lengths. The maximum of corresponding relative error is 0,15 ‰, while the minimum is 0,03 ‰.

In a word, seen from the two typical leak detection and location results of pressure wave signals, the suggested method is feasible. It not only enriches the application of intuitionistic fuzzy set theory in petroleum pipeline leak detection and location, but also possesses certain economic value in terms of practical petroleum pipeline online monitoring.

6 Conclusion

At present, the fuzzy rule decision-making and classification exhibits complexity in realizing petroleum pipeline leak detection and location; establishing fuzzy rules needs abundant domain expert knowledge; the rule base lacks completeness and universality. To overcome these shortcomings, this paper sets off from matching template sequences, and then proposes new practical method for petroleum pipeline leak detection and location which integrates intuitionistic fuzzy set similarity and intuitionistic fuzzy entropy on the basis of signal sequence power spectrum features. This promotes the application of intuitionistic fuzzy set theory in pipeline inspection.

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