Decision fusion framework in diagnostic and prognostic assessment of long-distance oil pipeline leakage and damage based on Dempster-Shafer theory

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Abstract: A decision fusion algorithm in diagnostic and prognostic assessment of long-distance oil pipeline leakage and damage based on Dempster-Shafer (D-S) theory is proposed in this paper. To monitor the leakage and external damage, a new monitoring system is constructed with an optical fiber cable installed along the pipeline as a distributed optical fiber sensor (DOFS) and a pair of pressure meters installed at the pipeline inlet and outlet. When leaking, the oil stream disturbs the cable and a negative-pressure wave originates which propagates to pipe inlet and outlet. The probability of leaking is evaluated according to the correlation coefficient of negative-pressure waves acquired at the inlet and outlet, and the location is pinpointed using the negative-pressure method. The optical fiber cable is sensitive to soakage of oil products and mechanical deformation/vibration caused by leaking, tampering, or mechanical impacting. An optical time domain reflectometry (OTDR) is employed to locate the additional attenuation and an optical power meter is employed to record the transmitted optical power. By using the D-S rule, features generated from the waveforms of optical power and negative-pressures are fused to make a decision about whether and where there is leakage and/or external damage.

1. Introduction

To monitor buried oil pipelines, a number of leak detection methods have been presented [1]. These methods fall into two categories: externally based (direct) and internally based (inferential). Direct methods, such as acoustic method and infrared thermography, as well as technologies like hydrocarbon sensing via optical fiber or dielectric cables, detect leakage by monitoring some particular physical measurand fields outside pipelines. Inferential methods infer the oil leakage by monitoring pipeline internal parameters (i.e., pressure, flow, temperature and etc.). On the other hand, some activities to steal oil by drilling holes on the buried oil pipelines may also be monitored through an optical fiber cable buried beneath the soil running along the pipeline, since the cable is capable of detecting a wide range of physical, mechanical, chemical parameters outside the pipeline, such as strain-stress, vibration, acoustic-emission, pressure and leaked hydrocarbon [2].

However, all methods listed above are limited to certain environment conditions and most of them include simple rules for alarming when the measured values change too rapidly or exceed the given thresholds. These simple rules often lead to miss-alarm or meaningless false alarms. To deal with this problem, a data fusion algorithm based on Dempster-Shafer (D-S) theory is presented to identify
and locate the leakage and external damage by integrating the real-time signals from pressure meters, flow meters, and distributed optical fiber sensors with the information about the historic maintenance status records of the pipe, the geological condition, and the pipe wall health condition. The rules-based logic reasoning will be a major enhancement in terms of reducing the number of false alarms and increasing the reliability and robustness.

This paper develops a new model based on D-S theory for oil pipeline leakage & damage detection. The D-S theory is introduced in Section 2. The implements of classifiers for detecting the leakage and external damage are described in Section 3. The decision fusion algorithm based on D-S rule is discussed in Section 4 and finally the conclusion is presented in Section 5.

2. Dempster-Shafer theory of evidence

As a method to deal with uncertain problems, the D-S theory provides a powerful tool to combine evidences from different classifiers and is more flexible than Bayesian decision theory when knowledge is incomplete. To apply D-S theory to the detection, the frame of discernment must be defined. Assume that \( a_1 \) is a primitive hypothesis representing the leak-occurrence, \( a_2 \) is a primitive hypothesis representing the damage-occurrence, and \( a_3 \) is the other hypothesis representing the unknown disturbance. The frame of discernment is \( \Theta = \{a_1, a_2, a_3\} \) and its power set is \( 2^\Theta = \{\phi, \{a_1\}, \{a_2\}, \{a_3\}, \{a_1, a_2\}, \{a_1, a_3\}, \{a_2, a_3\}, \{a_1, a_2, a_3\}\} \). The mass of evidence is defined as a mass function or basic probability assignment on the power set. The mass function must satisfy the following axiom.

\[
m(\phi) = 0, \quad \sum_{A \in \Theta} m(A) = 1
\]

Let \( m_x \) and \( m_y \) be two mass functions defined on the same frame of discernment. The combination of independent evidence in D-S theory is implemented using the Dempster’s rule [3], that is

\[
m(C) = K^{-1} \sum_{A \cap B = C} m_x(A) m_y(B)
\]

where the normalization constant \( K \) is given by

\[
K = 1 - \sum_{A \cap B = \phi} m_x(A) m_y(B)
\]

3. Detecting models

In real infrastructures of oil pipeline monitoring systems, there are many sensors, such as pressure meters and DOFS, shown in Figure 1. Each sensor records the waveform of a particular parameter and the corresponding processor unit classifies the waveform as a definite (true or false) or uncertain one, which includes the features of faults. Finally a probability \( m \) for belief in the classification is given.

3.1. Negative pressure method of leakage detection

Oil is usually transferred through a pipeline with high pressure. Once oil leaks, a negative pressure wave originates and then propagates along the pipeline to the inlet and outlet. Assume that \( P_{\text{in}}(t) \) and \( P_{\text{out}}(t) \) are the normalization waveforms of negative-pressure at inlet and outlet respectively. \( P_{\text{in}}(t) \) and \( P_{\text{out}}(t) \) are correlative because they originate from the same source. The leaking probability can be evaluated according to the following correlation coefficient of \( P_{\text{in}}(t) \) and \( P_{\text{out}}(t) \).

\[
r(\tau) = \int_{-\infty}^{\infty} P_{\text{in}}(t) \times P_{\text{out}}(t + \tau) dt \quad \tau \in [0, L/(v_p - v_o)]
\]
where \( L \) is the length of pipeline, \( v_p \) is the propagation speed of negative-pressure wave, and \( v_0 \) is the transmission speed of oil inside the pipeline. Assume that the \( r(\tau) \) reaches its maximum value when \( \tau = \tau_m \), the leakage probability, denoted as \( m_N(a_1) \), is given according to the following formula:

\[
m_N(a_1) = r(\tau_m)
\]

and then

\[
m_N(\emptyset) = 1 - r(\tau_m)
\]

\( \tau_m \) indeed is the time difference when the negative pressure arrives at the inlet and outlet. The distance \( l \) from the point of leakage to the pipeline inlet is evaluated according to the following formula:

\[
l = \frac{1}{2v_p} \left[ L(v_p - v_0) + (v_p^2 - v_0^2) \times \tau_m \right]
\]

### 3.2. Distributed optical fiber sensor for leakage and external damage detection

A smart and sensitive optical fiber cable is installed along the pipeline for monitoring the oil leakage and external damage. The cable is sensitive to soakage of oil products and a wide range of physical, mechanical and chemical parameters outside the pipeline. When exposed to oil or hydrocarbon liquids, the cable swells and induces additional attenuation inside the fiber. Furthermore, the attenuation is also sensitive to the deformation and vibration caused by leaking, tampering, or mechanical impacting. The additional attenuation can be detected and located by DOFS based on the optical time domain reflectometry (OTDR), and the types of external disturbance can be identified according to the characteristics of the transmitted optical power received by an optical power meter.

By launching a short and strong optical pulse into a fiber, and then measuring the backscattered optical power as a response of the fiber to the optical pulse, OTDR can correlate what it sees in backscattered light with an actual location on the fiber, thus the spatial variation of attenuation can be determined at any point on the fiber. On the other hand, the transmitted optical power \( O_{out} \) is

\[
O_{out}(t) = O_{0m} \times S(t) \times \exp\left(-\int_a^t a(x,t)dx\right)
\]

where \( O_{0m} \) is the power of the optical pulse, \( S(t) \) is the backscattering coefficient at time \( t \), \( a \) is attenuation coefficient and \( L \) is the length of optical fiber.

The \( O_{out}(t) \) is monitored in real time. Once the \( O_{out}(t) \) changes, the following cases maybe occur:

A. Decaying exponentially, which is caused by oil leaking;
B. Pulse - Down and then return to normal, which is caused by mechanical disturbances;
C. Oscillating, which is caused by mechanical disturbances or streams of oil leakage; and
D. Zero, which is caused by fiber break.

Therefore the frame of discernment of \( O_{out}(t) \) is \( \Omega = \{A, B, C, D\} \). A mass function \( m_o \) can be generated from an observed waveform \( O_{out}(t) \) of fault according to its features. With case \( A \) and \( C \) contributing to the primitive hypothesis \( a_1 \) of leak-occurrence, and case \( B \), \( C \) and \( D \) contributing to the primitive hypothesis \( a_2 \) of damage-occurrence, the mass function \( m_o \) on \( \Omega \) can be transformed into the mass function \( m_F \) on \( \Theta \) as following to simplify the problem [4].

\[
\begin{align*}
m_F(a_1) &= m_o(A) \\
m_F(a_2) &= m_o(B) + m_o(D) + m_o(B, D) \\
m_F(a_1, a_2) &= m_o(C) \\
m_F(\emptyset) &= 1 - m_F(a_1) - m_F(a_2) - m_F(a_1, a_2)
\end{align*}
\]

### 4. Decision fusion algorithm based on D-S theory

To make an assessment on long-distance oil pipeline leakage and external damage, the evidences associating with the waveform features of the transmitted optical power and the negative pressure are fused using Dempster’s rule. The combination result of the \( m_N \) and \( m_F \) is
By using the decision rule based on the basic probability assessments, the decision can be made. Assume that $A_1, A_2 \in \Theta$, $m(A_1) = \max\{m(A), A_1 \subset \Theta\}$, and $m(A_2) = \max\{m(A), A_1 \neq A \cap A_1 \subset \Theta\}$. If $A_1$ and $A_2$ satisfy the following relations, that is,

$$
\begin{align*}
& m(A_1) - m(A_2) > \varepsilon_1 \\
& m(\Theta) < \varepsilon_2 \\
& m(A_1) > m(\Theta)
\end{align*}
$$

the result of decision is $A_1$, where $\varepsilon_1$ and $\varepsilon_2$ are the given thresholds.

If $A_1 = \{a_1\}$, it means that oil is leaking. If $A_1 = \{a_2\}$, it means that there is an external damage on the pipeline. If $A_1 = \{a_1, a_2\}$, it means that there is a leakage while the leaking stream disturbs the sensing fiber cable. Otherwise if any of $\{a_1\}$, $\{a_2\}$ and $\{a_1, a_2\}$ does not satisfy the equation (12), it means that nothing happens. Table 1 shows the sample decision fusions of simulation evidences.

| $m_N(a_1)$ | $m_N(\Theta)$ | $m_F(a_1)$ | $m_F(a_2)$ | $m_F(a_1, a_2)$ | $m_F(\Theta)$ | $m(A_1)$ | $m(A_2)$ | $m(a_1, a_2)$ | $m(\Theta)$ | $A_1$ |
|------------|---------------|------------|------------|-----------------|---------------|---------|---------|----------------|-------------|------|
| 0.8        | 0.2           | 0.15       | 0.15       | 0.5             | 0.2           | 0.81    | 0.03    | 0.11           | 0.05        | $\{a_1\}$ |
| 0.2        | 0.8           | 0.15       | 0.15       | 0.5             | 0.2           | 0.30    | 0.12    | 0.41           | 0.17        | $\{a_1, a_2\}$ |
| 0.2        | 0.8           | 0.15       | 0.5        | 0.15            | 0.2           | 0.24    | 0.45    | 0.13           | 0.18        | $\{a_2\}$ |

5. Conclusion

A decision fusion algorithm in diagnostic and prognostic assessment of long-distance oil pipeline leakage and external damage is proposed based on the D-S theory. To monitor the leakage and external damage, a new monitoring system is constructed with a fiber cable installed as a distributed sensor along the pipeline and a pair of pressure meters installed at the pipes inlet and outlet. Each sensor records the waveform of a particular parameter and the corresponding processor unit classifies the waveform as a definite (true/false) or uncertain one including features of faults. By using the D-S rule, the waveform features from sensors are fused to make a decision, which may be true, false, or uncertain, about whether and where oil leakage and/or external damage happen. This method provides a powerful tool of combining measures of the evidences from different sensors to increase the reliability and the robustness of warning and to reduce the miss-alarm and meaningless false alarm.

References

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