TABLE III
COMPARISON WITH NBS AND CSIRO RELATIVE TO THE CAPACITOR BF350-50T

	Parameters	BF350-50T	SC-300 (NBS)	SC-330 (CSIRO)
Rating Voltage (kV)		350	300	330
Rating Capacitance (pF)		50	100	100
Eccentricity (10^{-6} m)		140 ± 15		650
Rigidity Coefficient (10^{-6} m/N)	Low-Voltage Electrode	4.67 ± 0.11		12.5
	High-Voltage Electrode	0.00 ± 0.05	1.02	
	Insulating Bushing	0.00 ± 0.22		1.25
$\left.\frac{\partial f(a)}{\partial a}\right\|_{a=a0}$ (10^{-12} F/m)		2.79	52.9	27
$\left.\frac{\partial f_2(a)}{\partial a}\right\|_{a=a2}$ (10^{-12} F/m)		2.13	52.9	27
$\Delta C_a/C$ (10^{-6})		0.04 ± 0.02	1.1	1.8

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Leak Detection for Transport Pipelines Based on Autoregressive Modeling

Guizeng Wang, Dong Dong, and Chongzhi Fang

***Abstract*—The detection and location of leaks in fluid transport pipelines often require flow measurements, which may be unavailable in practice. In this paper, a new leak detection method based on autoregressive modeling is proposed. It requires only four pressure measurements, two at each end of the pipeline. A leak above 0.5% can be reliably and quickly detected by analyzing the time sequences of the pressure gradient at the inlet and outlet of the pipeline. Furthermore, it can be easily implemented because the computational expenditure is small. Its effectiveness has been verified by tests on a 10 mm diameter, 120 m long experimental water pipeline.**

I. INTRODUCTION

With the development of the transport pipeline industry, more and more attention is paid to leak detection and location in operating transport pipelines. In the early stages, only some simple and direct methods were used, such as flow balance methods [1] and acoustic methods [2]. In the early 1980's, Siebert [3] and Billman *et al.* [4] proposed methods based, respectively, on parameter identification and state observation, which can give more accurate results. However, these methods require flow rate measurements which sometimes are not available in practice. In this paper, a new method of leak detection based on autoregressive modeling is proposed. It only requires pressure measurements, and is thus more practicable in some instances.

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II. BASIC CONCEPT

Let Z be the coordinate along the transport pipeline axis and p the pressure of fluid in the pipeline. If the flow rate is constant, the relationship between the pressure and flow rate is approximately as follows:

$$p(Z_1) - p(Z_2) = CQ^2(Z_2 - Z_1) \tag{1}$$

where $p(Z_1)$ and $p(Z_2)$ represent pressures at positions Z_1 and Z_2, respectively, Q is the flow rate, and C is a parameter. Assume that the medium in the pipeline is homogeneous; the temperature and friction coefficient do not change with coordinate Z and time t; then C is a constant. The pressure distribution along the pipeline is shown as a solid line in Fig. 1.

Let $p(O)$ and $p(L)$ be, respectively, the inlet and outlet pressure measurements of a pipeline; from (1), we can get

$$\frac{p(O) - p(Z)}{p(Z) - p(L)} = \frac{Z}{L - Z} \tag{2}$$

where L is the length of the pipeline. The left side of (2) is not dependent on Q.

When a leak occurs at position Z^* in the pipeline, then the pressure profile changes to the dashed line shown in Fig. 1. In this case, $[p(O) - p(Z^*)]/[p(Z^*) - p(L)]$ is not only related to Z^* and L, but is also dependent on the leak size as well.

In this proposed scheme, four pressure signals $p(O)$, $p(\Delta Z)$, $p(L - \Delta Z)$, and $p(L)$ are measured at positions O, ΔZ, $(L - \Delta Z)$, and L, respectively. A time sequence x_k can be devised as

$$x_k = \frac{p_k(O) - p_k(\Delta Z)}{p_k(\Delta Z) - p_k(L)} - \frac{p_k(L - \Delta Z) - p_k(L)}{p_k(O) - p_k(L - \Delta Z)} \tag{3}$$

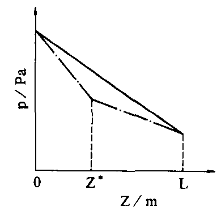

Fig. 1. Pressure distribution along pipeline.

where the subscript k implies the kth time instant. The x_k contains the information of the pressure gradients at both the upstream and downstream ends.

Note that the signal x_k is not dependent on Q, and will be equal to zero in the case when the flow rate is constant and no leak occurs in the pipeline. If there exists a stochastic disturbance in the flow process, x_k will be a random time sequence. Let x_k^0 and x_k^1, respectively, represent the random time sequences acquired under normal and leaking conditions at instant k. These time sequences can be fitted to AR (autoregressive) models whose parameters and residual variances are dependent on the particular conditions of the pipeline. Leaks can be detected by using Kullback information to analyze the parameters and residual variances [5], [6].

III. Leak Detection by Using Kullback Information

Kullback information is very useful in time sequence analysis.

The time sequences x_k^0 and x_k^1 are supposed to be stationary random sequences, and can be fitted to the following AR models[5]:

$$x_k^0 = \sum_{i=1}^{m} \varphi_i^0 x_{k-i}^0 + e_k^0, \qquad k = 1, 2, \cdots, n \tag{4}$$

$$x_k^1 = \sum_{i=1}^{m} \varphi_i^1 x_{k-i}^1 + e_k^1 \tag{5}$$

where m is the order of the AR model, e_k^j is a white Gaussian noise with zero mean and variance σ_j^2, and φ_i^j is the parameter of the AR model. $j = 0, 1$ represent the normal state and leaking state, respectively, and n is the length of the time sequences.

Let the joint probability density function of n-dimensional random variables $x_1^0, x_2^0, \cdots, x_n^0$ be $f_0(x_1, x_2, \cdots, x_n)$, and let the joint probability density function of n-dimensional random variables $x_1^1, x_2^1, \cdots, x_n^1$ be $f_1(x_1, x_2, \cdots, x_n)$. Then the Kullback information is given by the following equation [6]:

$$I(f_0, f_1) = \frac{1}{n}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\cdots\int_{-\infty}^{+\infty} f_0(x_1, x_2, \cdots, x_n) \cdot \ln\frac{f_0(x_1, x_2, \cdots, x_n)}{f_1(x_1, x_2, \cdots, x_n)}\, dx_1\, dx_2 \cdots dx_n. \tag{6}$$

Since

$$f_j(x_1, x_2, \cdots, x_n) = f_j(e_n) f_j(e_{n-1}) \cdots f_j(e_1),$$

therefore

$$\begin{aligned} I(f_0, f_1) &= (1/n)E_0\Big\{\ln\prod_{k=1}^{n}[(1/\sqrt{2\pi}\sigma_0)\exp[-(x_k - \varphi_1^0 x_{k-1} - \cdots - \varphi_m^0 x_{k-m})^2/2\sigma_0^2]]/[(1/\sqrt{2\pi}\sigma_1) \cdot \exp[-(x_k - \varphi_1^1 x_{k-1} - \cdots - \varphi_m^1 x_{k-m})^2/2\sigma_1^2]]\Big\} \\ &= \ln\frac{\sigma_1}{\sigma_0} - \frac{1}{2\sigma_0^2 n}\sum_{k=1}^{n} E_0[(x_k - \varphi_1^0 x_{k-1} - \cdots - \varphi_m^0 x_{k-m})^2] \\ &\quad + \frac{1}{2\sigma_1^2 n}\sum_{k=1}^{n} E_0[(x_k - \varphi_1^1 x_{k-1} - \cdots - \varphi_m^1 x_{k-m})^2]. \end{aligned} \tag{7}$$

E_0 denotes the expectation of the time sequence x_k^j with respect to $f_0(x_1, x_2, \cdots, x_n)$:

$$\begin{aligned} E_0[(x_k - \varphi_1^0 x_{k-1} - \cdots - \varphi_m^0 x_{k-m})^2] \\ = E[(x_k^0 - \varphi_1^0 x_{k-1}^0 - \cdots - \varphi_m^0 x_{k-m})^2] = \sigma_0^2 \end{aligned} \tag{8}$$

$$\begin{aligned} E_0[(x_k - \varphi_1^1 x_{k-1} - \cdots - \varphi_m^1 x_{k-m})^2 \\ = E[(e_k^0 + (\varphi_1^0 - \varphi_1^1) x_{k-1}^1 + \cdots + (\varphi_m^0 - \varphi_m^1) x_{k-m}^0)^2] \\ = \sigma_0^2 + [\Phi_0 - \Phi_1]^T R_0 [\Phi_0 - \Phi_1]. \end{aligned} \tag{9}$$

R_0 is a correlation matrix, and Φ_0 and Φ_1 are parameter vectors of the AR models under their respective conditions:

$$R_0 = \begin{bmatrix} r_0(0) & r_0(1) & \cdots & r_0(m-1) \\ r_0(1) & r_0(0) & \cdots & r_0(m-2) \\ \cdots & \cdots & \cdots & \cdots \\ r_0(m-1) & r_0(m-2) & \cdots & r_0(0) \end{bmatrix}$$

$$r_0(i) = E[x_k^0, x_{k-i}^0], \qquad i = 0, 1, \cdots, m-1$$

$$\Phi_0 = [\varphi_1^0, \varphi_2^0, \cdots, \varphi_m^0]^T, \ \Phi_1 = [\varphi_1^1, \varphi_2^1, \cdots, \varphi_m^1]^T. \tag{10}$$

Substituting (8) and (9) into (7) yields

$$I(f_0, f_1) = \frac{1}{2}\left\{\ln\frac{\sigma_1^2}{\sigma_0^2} - 1 + \frac{1}{\sigma_1^2}[\sigma_0^2 + (\Phi_0 - \Phi_1)^T R_0 (\Phi_0 - \Phi_1)]\right\}. \tag{11}$$

Similarly, we can get

$$I(f_1, f_0) = \frac{1}{2}\left\{\ln\frac{\sigma_0^2}{\sigma_1^2} - 1 + \frac{1}{\sigma_0^2}[\sigma_1^2 + (\Phi_0 - \Phi_1)^T R_1 (\Phi_0 - \Phi_1)]\right\} \tag{12}$$

where R_1 is a correlation matrix:

$$R_1 = \begin{bmatrix} r_1(0) & r_1(1) & \cdots & r_1(m-1) \\ r_1(1) & r_1(0) & \cdots & r_1(m-2) \\ \cdots & \cdots & \cdots & \cdots \\ r_1(m-1) & r_1(m-2) & \cdots & r_1(0) \end{bmatrix}$$

$$r_1(i) = E[x_k^1, x_{k-i}^1], \qquad i = 0, 1, \cdots, m-1. \tag{13}$$

Because Kullback information does not have a symmetric property, a Kullback divergence function $P_f = I(f_0, f_1) + I(f_1, f_0)$ is pro-

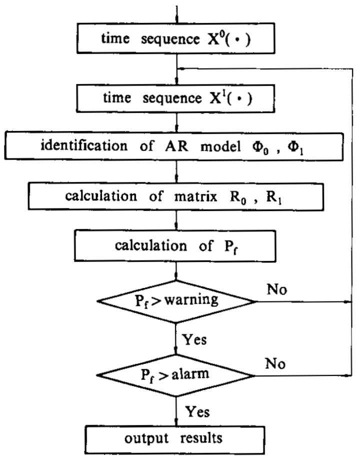

Fig. 2. Flowchart of real-time leak detection procedure.

posed as a performance index of leaking [8], [9]:

$$P_f = \frac{1}{2\sigma_1^2}\{\sigma_0^2 + [\Phi_0 - \Phi_1]^T R_0 [\Phi_0 - \Phi_1]\}$$

$$+ \frac{1}{2\sigma_0^2}\{\sigma_1^2 + [\Phi_0 - \Phi_1]^T R_1 [\Phi_0 - \Phi_1]\} - 1. \quad (14)$$

It is apparent that $P_f \geq 0$. When these two time sequences have the same statistical characteristics, $P_f = 0$. If a leak occurred, x_k^1 would be different from x_k^0, and Φ_1 and σ_1^2 different from Φ_0 and σ_0^2, which lead to $P_f > 0$.

The flowchart of a real-time leak detection procedure is shown in Fig. 2. Four steps are included.

1) Acquisition of time sequences x_k^0 and x_k^1.

2) AR model identification.

3) Correlation function calculation. The correlation function $r_j(i)$ is estimated by

$$\hat{r}_j(i) = \frac{1}{n}\sum_{k=0}^{n-1} x_k^j x_{k-i}^j,$$

and the recursive form of the calculation of $r_j(i)$ is as follows [10]:

$$\hat{r}_j(i, k) = (1 - \psi)\hat{r}_f(i, k-1) + \psi(x_k^j x_{k-1}^j)$$

where ψ is a forgetting factor, $0.9 < \psi < 1.0$.

4) Calculation of P_f. It can be calculated by (14).

A leak alarm will be triggered when P_f is beyond the preset threshold.

IV. Test Results

The method proposed in this paper has been verified on a 10 mm diameter, 120 m long experimental water pipeline. A schematic layout of the experimental pipeline system is shown in Fig. 3. The pipeline lies horizontally. At the upstream end of the pipeline are two pumps in series. Four pressure sensors with 0.2% precision are installed at positions 0, 20, 100, and 120 m from the upstream end. Along the pipeline, there are several points which can be used to develop a leak. A microcomputer IBM-PC/XT with a 12-b A/D converter is used for data acquisition and data processing. The sampling period is set at 20 ms, the order of AR models $m = 5$, the length of the time sequences $n = 2000$, and the forgetting factor $\psi = 0.95$. The test results are given in Figs. 4–6. Fig. 4 shows the

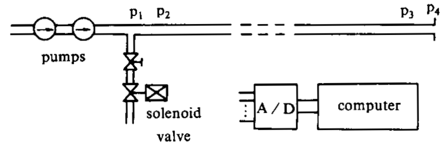

Fig. 3. Schematic layout of the experimental water pipeline system.

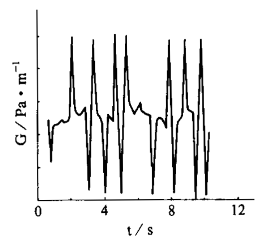

Fig. 4. Pressure gradient at upstream end.

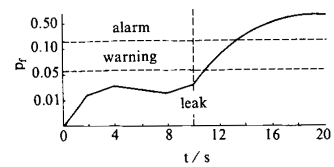

Fig. 5. Performance index P_f versus time (1% leak).

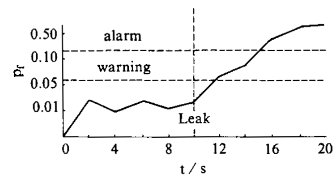

Fig. 6. Performance index P_f versus time (0.5% leak).

pressure gradient signal $[p(0) - P(\Delta Z)]$ at the upstream end. Fig. 5 shows the performance index P_f versus time when a 1% leak occurred at $t = 10$ s. Fig. 6 shows the performance index P_f versus time for a 0.5% leak.

V. Conclusions

The test results illustrate the effectiveness of the proposed leak detection method. A 0.5% leakage can be reliably and almost instantly detected by this method. Since this method does not require flow rate measurement, it is more practical in many instances. The basic idea of using autoregressive models for leak detection can be used for other fault detections as well.

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Precision Average-Sensing AC/DC Converters

Olev Märtens and Toom Pungas

***Abstract*—Various configurations of average-sensing ac/dc converters for precision ac voltage measurements are described. Due to the unique electrical configurations in which the influence of the inaccuracy of ratio resistors is suppressed, these converters have high accuracy (better than 0.01%) and resolution (0.0001%) at medium frequencies. Their frequency range is from 10 Hz to 1 MHz, with a settling time less than 1 s.**

I. Introduction

Conventional average-sensing ac/dc converters include a half-wave or a full-wave operational rectifier and a low-pass filter. Conversion is achieved there by switching resistors in the negative feedback path of an operational rectifier (for example, by diode switches) to obtain +1 and −1 gains during positive and negative half-waves [1]. The main disadvantage of such converters is that the conversion accuracy directly depends on the accuracy of resistor ratios. These converters are also quite complex, as they include a low-pass filter and often a means to suppress the offset voltage.

ac/dc conversion may also be performed using the idea of switching a capacitor (capacitors) in the negative feedback path of an op-amp. In such converters, due to circuit asymmetry for both half-waves, direct voltage is generated on a capacitor (capacitors), proportional to the input ac signal [2], [3].

The idea of switching capacitors makes it possible to design average-sensing ac/dc converters, which perform the conversion of the input alternating voltage into alternating current, and the conversion of the rectified current into output direct voltage on the same resistors. The transfer errors of these converters depend weakly on the resistor ratio errors.

II. Proposed AC/DC Converters

A. Half-Wave Converter

The half-wave ac/dc converter is shown in Fig. 1. The ac input voltage drops on the input resistor R_2 because the other end of R_2 is at the virtual ground potential, connected via the capacitor C_2 to the inverting input of the op-amp A_1. The negative feedback path includes the capacitor C_3, the diode VD_1, and the capacitor of C_1, during the positive half-waves of the input signal, or the diode VD_2, during the negative half-waves. The input bias current of the op-amp may be neglected because its ratio to the nominal value of the rectified current is smaller than 1/1 000 000; the alternating current in R_2 must flow to the output of the amplifier, and is rectified by VD_1 and VD_2. The direct component of the current flowing through VD_2 may flow only through R_2, as the rest of the circuit is separated by C_2 and C_3. In effect, the dc voltage drop on the resistor R_2 is proportional to the average value of the rectified input voltage.

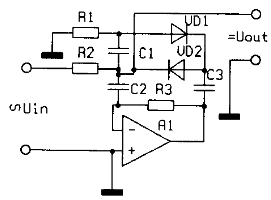

Fig. 1. A half-wave ac/dc converter.

The transfer coefficient of this converter is

$$K = (U_{out}/U_{in}) = 0.5 \tag{1}$$

where U_{out} is the value of the output direct voltage, and U_{in} is the average value of the rectified input ac voltage.

Resistor R_3 in this configuration, as well as in the following configurations, is providing the operation of the op-amp at dc. This resistor must have a large value, as for ac it is switched in parallel to the reverse resistances of the diodes.

High accuracy and stability of the transfer coefficient of this converter are achieved by converting the input ac voltage into the ac current, and converting the rectified current into the output dc voltage on the same resistor. An advantage of this converter is also suppression of the ripple voltage by the converter itself because for the ac, the inverting input of the op-amp is connected to the output of the converter. The circuit has no offset error because the op-amp works as an ac amplifier only, and is fully separated by capacitors from the output.

B. Full-Wave Rectifier

The full-wave converter shown in Fig. 2 works in a similar way. However, the transfer coefficient of this converter is higher, as the rectified ac current is not determined by the conductance of one resistor, but by the conductance of two resistors R_1 and R_2 connected in parallel. The output direct voltage is generated on the capacitor C_2, and the transfer coefficient is determined by the ratio of the resistor R_2, on which the rectified current generates the output voltage, to the parallel resistance of R_1 and R_2. The transfer coefficient of this converter is

$$K = (U_{out}/U_{in}) = 0.5 * (1 + R_2/R_1). \tag{2}$$

If the resistors R_1 and R_2 have the same nominal values, then the resistor ratio may be expressed using the value of the relative inaccuracy of the ratio R_2/R_1:

$$R_2/R_1 = 1 + \delta r. \tag{3}$$

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