The Application Research of the Natural Gas Pipeline Leakage Detection Based on Adaptive Time Frequency Analysis

Xiufang Wang, Bojian Li, Renxue Tan, and Qing Wang
School of Electrical Information Engineering, Northeast Petrolum University, Daqing, China
Email: {wxfdqpi, wwwjianjiancn, trx19920127, wqq8392}@163.com

***Abstract*—The infrasonic wave signal that produced by the leakage of natural gas pipelines is a non-stationary signal. When the infrasonic waves signal propagating in pipes, it will get serious interference by external Environment, resulting in high misjudgment rate of leakage. So a new method detecting the leakage of natural gas pipelines was put forward according to the leak acoustic signal feature. This method is based on adaptive optimal kernel time-frequency analysis algorithm, through the short-time ambiguity function and the adaptive optimal kernel with time changing, achieve the time-frequency acoustic signal processing and the accurate judgment of pipeline leak acoustic signal when the pipeline is leaked.**

***Index Terms*—pipeline leak, infrasonic wave, adaptive optimal kernel, time-frequency analysis**

I. Introduction

With the development of pipeline transportation industry, pipeline safety problem is becoming more and more important. People have to pay more and more attention on natural gas pipeline leak detection. In the past few decades, people put forward many kinds of pipeline leak detection methods, such as flow balance method [1] ultrasonic detection method [2], statistical decision method [3], optical fiber sensor method [4], negative pressure wave method and so on [5]. Although they have many desirable place for the leak detection, but they still have many problems, such as not in real time on the long distance pipeline monitoring, Complex installation, high cost, can't detect small leakage, can't detect the location or orientation is not accurate.

Now, more attention has been paid on the natural gas pipeline leak detection method based on acoustic wave [6], research shows that pipeline leak detection method based on infrasonic wave, not only can monitor the pipeline micro leakage by real time, but also real-time monitoring long distance pipeline. It also has the advantages of convenient installation, high positioning accuracy, and can distinguish between leakage and other external interferences etc. However, when the pressure within the gas pipeline is low and the leakage is small. Because of the existence of outside interface and attenuation of acoustic wave in the propagation process of the pipeline within the lower pressure, resulting in infrasound wave that infrasound sensors received contains a lot of noise, increasing the difficulty of small leakage detection. In order to monitor the tiny leakage signal and eliminate the interference, we need to describe the time characteristics of acoustic signal in the pipeline through a suitable algorithm. Wigner-Ville distribution can well describe the time frequency distribution characteristics of non-stationary signals, have the very good application on Fault diagnosis and Short circuit detection [7], [8]. Yang Hongying, Ye Hao and so on try the Wigner-Ville distribution in pipeline leakage detection based on sound wave firstly in 2011 [9]. But the Wigner-Ville distribution of the cross-interference terms has a serious effect on signal. So In this paper, we have achieved real-time processing of sound signal in the pipe by using an adaptive optimal kernel time-frequency distribution.

II. The Anslysis of Adaptive Optimal Kernel

A. Wigner-Ville Distribution (WVD)

Infrasound signal of the pipeline leakage belongs to non-stationary random signal. In a lot of time-frequency analysis theories, The WVD distribution have great advantages on signal processing of the infrasound signal generated by the pipeline leakage [10].

The WVD distribution is [11]:

$$\begin{aligned} WVD(t, f) &= \int_{-\infty}^{+\infty} R_s(t,\tau) e^{-j2\pi f\tau} d\tau \\ &= \int_{-\infty}^{+\infty} s(t+\frac{\tau}{2}) s^*(t-\frac{t}{2}) e^{-j2\pi f\tau} d\tau \end{aligned} \tag{1}$$

If make the Fourier inverse transform for the autocorrelation function $R_s(t,\tau)$ about time factor "*t*", you can get another two-dimensional time-frequency distribution function [12], fuzzy function $AF(\tau,\nu)$:

$$AF(\tau,\nu) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} s(t+\frac{\tau}{2}) s^*(t-\frac{\tau}{2}) e^{j2\pi\nu t} dt \tag{2}$$

Viewing from the definition of WVD and fuzzy function, you will find both of them are about a linear transform of the autocorrelation function, the relationship between them is:

Manuscript received June 10, 2015; revised September 8, 2015.

doi: 10.18178/ijsps.4.4.334-338

$$WVD(t,f)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}AF(\tau,\nu)e^{-j2\pi(t\nu+\tau f)}d\tau d\nu \quad (3)$$

But for the signal that contains a variety of components, there are many cross-interferences in the WVD distribution. As shown in Fig. 1. The simulation of a segment composite signal that composed by two linear FM signal after WVD transform, generating serious cross-interference term between the two Original signals.

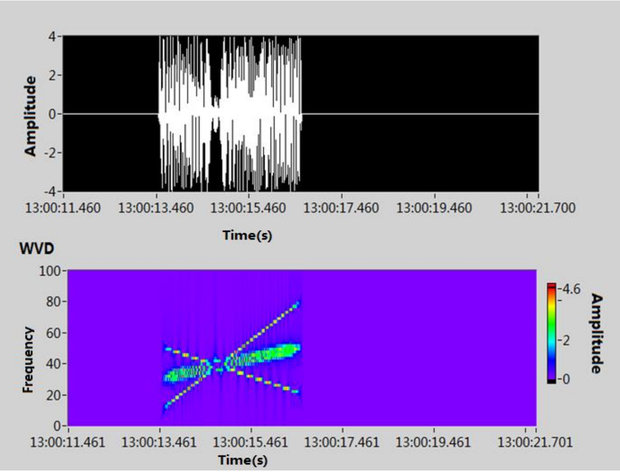

Figure 1. The WVD time-frequency distribution.

In order to restrain the cross-interference, many researchers have made many important improvements on the WVD, And Cohen have made a unified definition for these improvements.

$$p(t,f)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}AF(\tau,\nu)\Phi(\tau,\nu)e^{-j2\pi(t\nu-\tau f)}d\tau d\nu \quad (4)$$

$\phi(\tau,\nu)$ is the kernel function that used to control the cross-interference in the Wigner-Ville distribution, But a fixed kernel functions is only suitable for a specific type of signal Time-frequency distribution, it can restrain the cross-interference and enhance the original signal, and get accurate time-frequency distribution; But for other types of signals, due to the lack of adaptive ability for different types of signals, the effect is actually unsatisfactory. In order to solve this problem, the researchers proposed adaptive time-frequency distribution based on the previous researches.

B. Adaptive Time-Frequency Analysis

Adaptive time-frequency distribution include adaptive time-frequency distribution based on the matching pursuit algorithm (matching pursuit); adaptive short-time Fourier transform (adaptive STFT), and Radial Gauss kernel time frequency distribution (RGOK) etc. Radial Gauss kernel time frequency distribution in the fuzzy domain can effectively extract the original signal and restrain cross-interferences. So that it can effectively restrain cross-interferes in the time-frequency domain, describing the original signal prominently [13].

Radial Gauss kernel time-frequency distribution defines the kernel function that to be solved as two-dimensional Gauss function with arbitrary profile along the radial profiles:

$$\phi(\tau,\nu)=e^{-\frac{\tau^2+\nu^2}{2\sigma(\psi)}} \quad (5)$$

Design a Kernel function matching the signal to find the optimal kernel function, which is transformed into solving the optimization problems:

$$\max=\int_0^{2\pi}\int_0^{2\pi}\left|AF(r,\psi)\phi(r,\psi)\right|^2 rdrd\psi \quad (6)$$

The constraint conditions:

$$\begin{cases}\phi(t,\nu)=e^{-\frac{r^2}{2\sigma(\psi)}} \\ \frac{1}{2\pi}\int_0^{2\pi}\int_0^{\infty}\left|\phi(r,\psi)\right|^2 rdrd\psi=\frac{1}{2\pi}\int_0^{2\pi}\sigma^2(\psi) \quad d\psi\le\alpha\end{cases} \quad (7)$$

α is the volume of the kernel function. The value is $1\le\alpha\le5$.

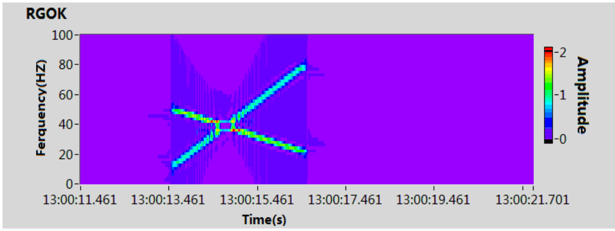

Figure 2. Mixed signal of the radial Gauss kernel time frequency distribution.

Fig. 2 is the radial Gauss kernel time-frequency transform of original signal. Compare with Fig. 1, you can find the cross-interference of time-frequency distribution is filtered out basically, and can well reflect the characteristic of signal time-frequency changing.

C. Adaptive Optimal Kernel Time-Frequency Analysis

RGOK is a global algorithm, just design a kernel function for the whole signal, But is doesn't suitable for the analysis of the signals that have the characteristics of time-varying. Idea that came up with AOK by Jones is a good solution for this problem [7]. The specific principle is: Define short-time ambiguity function

$$AF(t;\tau,\nu)=\int_{-\infty}^{+\infty}s(u+\frac{\tau}{2})w(u-t+\frac{\tau}{2})s^*(u-t-\frac{\tau}{2})e^{-2j\pi ft}du \quad (8)$$

In this Formula, $w(u)$ is the symmetric window function that regards t as the center, t_w is the window length, when $|u|>t_w$, $w(u)=0$, then use the formula (6) and (7) to compute the optimal kernel $\phi(t;\tau,\nu)$. So the signal adaptive optimal kernel time-frequency distribution in the time $[t-T,t+T]$ is:

$$p_{AOk}(t,f)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}AF(t;\tau,\nu)\phi(t;\tau,\nu)e^{-2j\pi(t\nu-\tau f)}d\tau d\nu \quad (9)$$

The kernel function of AOK can adapt the local features of the signal with time changing. It has more obvious improvement on the description of the non-stationary signal details than RGOK. As shown in Fig. 3, comparing with time-frequency distribution in Fig. 2, AOK has better time-frequency Aggregation and can completely eliminate the cross-interference of the signal.

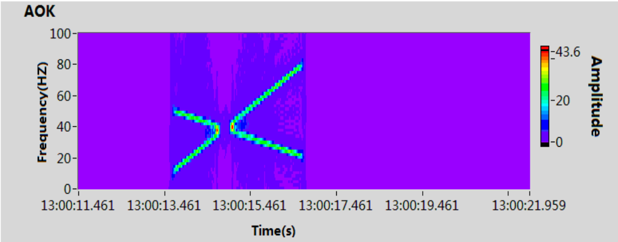

Figure 3. Mixed signal of the adaptive optimal kernel time-frequency distribution.

III. The Simulation Analysis of Example

In order to verify the advantages of AOK that can be applied in pipeline leak detection. We collect the real leakage signal in natural gas pipeline for simulation of signal leakage. Verify the adaptive optimal kernel time-frequency distribution in pipeline leakage detection that can judge the status of the pipeline leakage very well

A. The Experiment Analysis

The signals in Fig. 4 and Fig. 5 are the acoustic signals under different levels of leakage which are collected with infrasonic wave sensor on the simulation of natural gas pipeline in the laboratory. The simulate pipeline is 130 meters in length and the diameter is DN15. When pipeline leakage simulation experiment is carried out, the pipe gas pressure is 0.45 MPa, and there is no other interference noise in the pipeline. The diagram about specific laboratory simulation pipeline is showed in Fig. 6, the distance from leakage points to sound sensor is 70 meters. In Fig. 4, the signal is the simulation signal of gas leakage, and then the sensor receives the leakage signal. Actually, we install a ball valve with diameter is 4mm and a plug that leakage aperture about 1mm at the end of valve. On the data acquisition stage with a ball valve opening and closing ,the valve is opened only 1/4 during the opening process, we can see the begin and finish of leakage and the status of leakage signal on the original sonic data. The collection of data lasts 28 seconds. The distance from leakage points to sound sensor is 70 meters.

In Fig. 5, the signal is the simulation of gas leakage with an improvement at the leak point. The leakage signal collected by the sensor. In fact, the natural gas pipeline is very long, and the propagation of sound wave in pipeline has strong attenuation. In order to avoid vibration due to the process of opening and closing valve, and let the sensor only receive the acoustic wave that propagated by the medium of gas. So at the leak point we install a 10 meter high pressure acoustic attenuation soft tube on the pipe. And then at the end of acoustic attenuation soft tube we will install a ball valve with diameter is 4mm and a plug that leakage aperture about 1mm. On the data acquisition stage with a ball valve opening and closing, The valve is opened only 1/4 during the opening process, The collection of data lasts 45 seconds, but can't see the begin and finish of leakage and the status of leakage signal from the original sonic data.

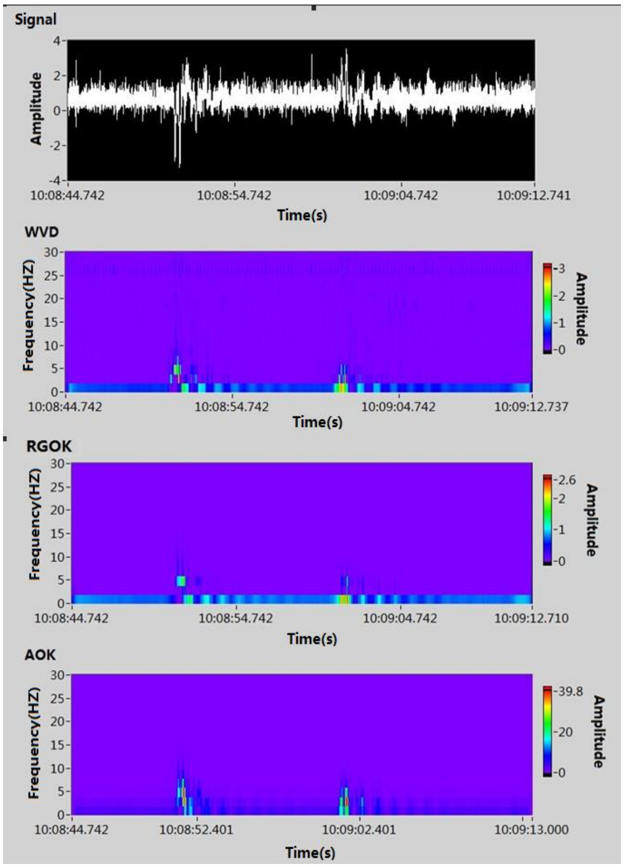

Figure 4. The time-frequency distribution of experimental data one.

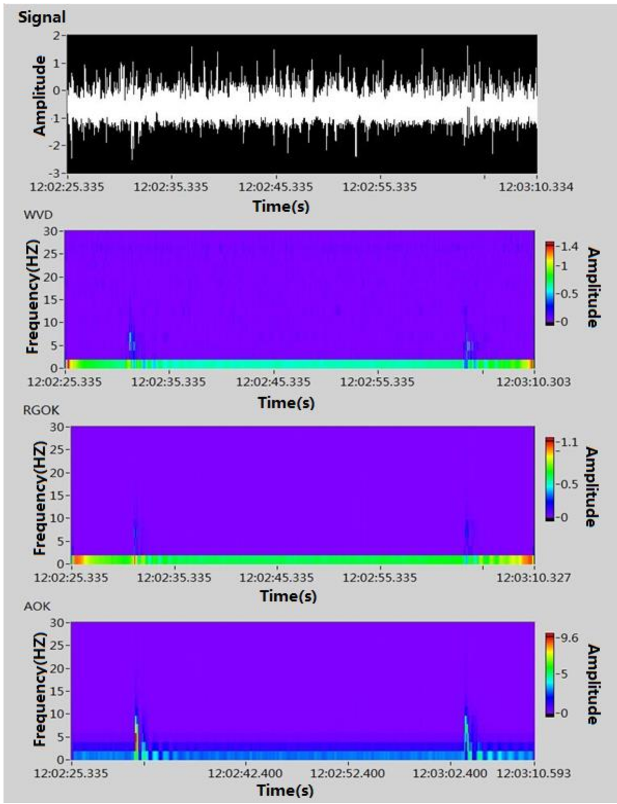

Figure 5. The time-frequency distribution of experimental data two.

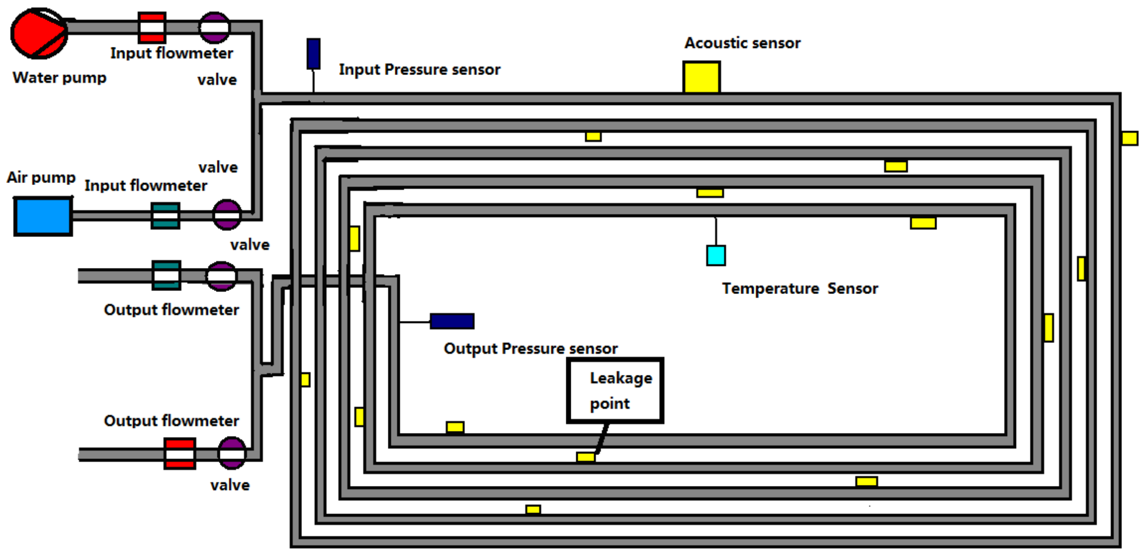

Figure 6. The experimental equipment of pipeline leakage.

It can be found through the time-frequency analysis on the data of sound wave with two different leakage conditions that larger leakage or smaller leakage, time-frequency analysis technology can exactly express the time-frequency characteristics of the infrasonic wave signals generated by the pipeline leakage, and you can clearly determine the time of happen and end of the pipeline leak. But under different time-frequency distributions, there are different advantages in the time-frequency aggregation, suppression Cross-Interference, Frequency Resolution, Anti-interference. According to the practical analysis, the performance comparison of various time-frequency distributions is shown in Table I:

TABLE I. T PERFORMANCE COMPARISON OF VARIOUS TIME FREQUENCY DISTRIBUTION

Time-frequency distribution	WVD	RGOK	AOK
Time-frequency aggregation	Less strong	weak	strong
suppression Cross-Interference	weak	Less strong	strong
Frequency Resolution	Less strong	weak	strong
The ability of Anti-interference	weak	Less strong	strong

B. Conclusions

By studying the three typical time-frequency analysis methods, we can find that WVD's cross inhibition ability, anti-interference ability are weak. Although RGOK can inhibit cross-terms and has stronger anti-interference ability, but it is weak in time-frequency clustering and frequency resolution ability; AOK is the best in all aspects of the performance. Because the sound signals generated by the leakage of pipeline are transient and non-stationary, it has low frequency characteristics. So the choice of time-frequency analysis method must have stronger frequency resolution and time-frequency clustering ability, and it can accurately distinguish the time of frequency change. Therefore, the leakage of pipeline detection technology based on sound with AOK is able to accurately determine whether pipeline leakage or the leakage time. It has an important application value.

ACKNOWLEDGMENT

Supported by Postdoctoral Foundation of Heilongjiang Province (LBH-Q13036).

Supported by Educational and Scientific Research Project of Educational Committee of Heilongjiang Province (12541063).

REFERENCES

[1] D. Li, C. Wang, Z. Shi, *et al.*, "The study and quantitative analysis of pipeline defect detection on ultrasonic," *Chinese Journal of Scientific Instrument*, no. 2, 2002.

[2] J. Zhang and M. Twomey, "Statistical pipeline leak detection techniques for all operating conditions," in *Proc. 26th Environment Symposium & Exhibition*, California, March 27-30, 2000.

[3] M. Alistair, M. Chris, J. Walter, *et al.*, "Detection of hydrocarbon fuel spills using a distributed fibre optic sensor," *Sensors and Actuators A*, vol. 109, no. 1, pp. 60-67, 2003.

[4] A. Wike, "SCADA based leak detection system," *Pipeline & Gas Journal*, vol. 213, no. 6, pp. 16-20, 1986.

[5] J. Yang and G. Wang, "The leakage diagnosis technology of natural gas pipeline," *Control and Instruments in Chemical Industry*, 2004.

[6] H. Ye, G. Wang, *et al.*, "Gas pipeline leakage detection and location technology based on acoustic signal," *Journal of Huazhong University of Science and Technology (Natural Science Edition)*, pp. 181-183, 2009.

[7] J. A. Rosero, L. Romeral, J. A. Ortega, *et al.*, "Short-Circuit detection by means of empirical mode decomposition and Wigner-Ville distribution for PMSM running under dynamic condition," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 11, pp. 4534-4547, 2009.

[8] B. Trajin, M. Chabert, J. Regnier, and J. Faucher, "Wigner distribution for the diagnosis of high frequency amplitude and phase modulations on stator currents of induction machine," in *Proc. IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives*, 2009, pp. 1-6.

[9] H. Yang, H. Ye, S. Zhai, *et al.*, "Leak detection of gas transport pipelines based on Wigner distribution," in *Proc. IEEE International Symposium on Advanced Control of Industrial Processes*, 2011, pp. 258-261.

[10] Y. Li, J. Wang, and F. Lei, “The application of adaptive optimal kernel time-frequency distribution on suppressing the cross terms,” *Systems Engineering and Electronics Nuclear*, 2004.
[11] D. L. Jones and R. G. Baraniuk, “An adaptive optimal-kernel time-frequency representation,” *IEEE Transactions on Signal Processing*, vol. 43, 1995.
[12] X. Liu, H. Wang, S. Zhao, J. Chen, J. Wei, and Q. Liu, “Application of adaptive optimal kernel time-frequency representation in reservoir prediction,” *Journal of Central South University (Natural Science Edition)*, vol. 43, pp. 3114-3120, 2012.
[13] Y. Zhang, “A new method technology research for pipeline leak detection,” Tianjin University, 2009

Xiufang Wang was born in Hebei Province, China in 1967. She obtained the B.S. degree on Electronic Technology Application from China University of Petroleum (East China), Qingdao, China, in 1988. She obtained M.S. degree on Power Electronic Technology from Harbin Institute of Technology, Harbin, China, in 1993. She obtained Ph.D. degree on Oil-Gas Storage and Transportation Engineering from Northeast Petroleum University, Daqing, in 2008. She was a Professor of the Northeast Petroleum University. Currently, her research interest focuses on signal processing of oil-gas.

Bojian Li was born in Heilongjiang Province, China in 1992. He received the Bachelor’s degree on Communication Engineering from The Northeast Petroleum University, Daqing, in 2014. Now he is currently working towards the Master’s degree in information and communication engineering at the College of Electronic Engineering, Northeast Petroleum University, China. His research interest includes modern communication system, information processing technology and signal processing.

Renxue Tan was born in Heiongjiang Province, China in 1992. She is maior in the information and communication engineering at the College of Electronic Engineering, Northeast Petroleum University, China.for Bachelor’s degree. Her research interest includes modern communication system and information processing technology.

Qing Wang was born in Chongqing Province, China in 1989. He received the Bachelor’s degree on Communication Engineering from The Northeast Petroleum University, Daqing, in 2012. Now he is currently working towards the Master’s degree in information and communication engineering at the College of Electronic Engineering, Northeast Petroleum University, China. His research interest includes modern communication system, information processing technology and signal processing.