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Study on leak-acoustics generation mechanism for natural gas pipelines

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ABSTRACT

In order to figure out the principles of acoustic leak detection for natural gas pipelines, a study on the leak-acoustics generation mechanism is carried out. The aero-acoustics generation mechanism is analyzed and when leakage occurs the wave equations of sonic sources are developed. The leak-acoustics generated by the quadrupole and dipole sonic sources are then simulated to obtain the laws of the acoustic characteristics. The simulation data are compared with the experimental data to verify the simulation accuracy under variable operating conditions. The results show that the quadrupoles and the dipoles generated by turbulent fluctuations cause leak-acoustics; the main component of pressure perturbations acquired by the dynamic pressure sensor is acoustic perturbations; both the simulation method and the experimental method can be applied to study the leak-acoustics generation mechanism of natural gas pipelines.

1. Introduction

Pipelines are used for natural gas transportation from fields to consumers. With the rapid development of natural gas pipelines, leakages occur occasionally, causing great energy waste and environmental pollution. Leak detection is an important way to protect pipelines from failure and to decrease the risks. The leak detection and location must be executed timely and accurately. Currently, the methods and systems for gas pipelines leak detection have been developed and studied. Typical such methods are based on mass/volume balance, negative pressure, transient model, acoustics, etc. The negative pressure method is based on measuring the absolute pressure change by pressure sensors, while the traditional acoustic method is based on measuring the acoustic pressure. The acoustic method proposed here is based on the measurement of pressure perturbations by dynamic pressure sensors. The leakage signal recorded by the dynamic sensor is an acoustic pressure drop not the acoustic pressure itself. This is termed pressure perturbation in the paper, which means the leakage acoustic pressure drop. The leakage-drop and other acoustics generated in the natural gas pipelines are called leak-acoustics. Therefore, the acoustic method can contribute to a more sensitive leak detection than negative pressure method, and a more concise leak detection than traditional acoustic method. Compared with other methods (Buerck et al., 2003; Lay-Ekuakille, Vendramin, & Trotta, 2009; Murvay & Silea, 2012), acoustic method (Watanabe & Himmelblau, 1986) has many advantages over them, such as higher sensitivity, more accurate leak location, etc. These can be seen clearly in Table 1.

The evaluation indexes in Table 1 are clarified as follows and the choice order of the method in the view of the evaluation index is listed in the table:

(1) Sensitivity means the least leakage rate which can be detected by the leak detection method when leakage occurs. In this view, the distributed optical fiber method and the proposed acoustic method is the first choice.
(2) Location accuracy is the proportion of the absolute value to the pipeline length and the absolute value comes from the located leakage point by the leak detection method minus the actual leakage point.
(3) False alarms mean the detection method alarms leakage while the leakage does not occurs.
(4) Missing alarms mean the detection method does not alarm leakage while the leakage does occur.
(5) Detection time is the time the leak detection method takes to locate the leakage point from the leakage occurring.
(6) Adaptability capacity is the applicability of the leak detection method when the operating conditions or medium of pipelines are variable.

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Nomenclatures

a_0	Velocity of sound outside the flow, m/s
a_1	Propagation velocity of acoustic wave in the section of pipeline ($0 \to x$), m/s
a_2	Propagation velocity of acoustic wave in the section of pipeline ($x \to L$), m/s
c_1	The average velocity of the fluid in the section of pipeline ($0 \to x$), m/s
c_2	The average velocity of the fluid in the section of pipeline ($x \to L$), m/s
f	Generalized function
F	The volume force effect on the fluid
L	The distance between upstream and downstream sensors, m
p	Pressure of natural gas, Pa
p_0	The undisturbed pressure of flow field or the average pressure of flow field, Pa
t	Flow time, s
Δt	The time interval between upstream and downstream sensors received, s
T_{ij}	The Lighthill stress tensor
$\vec{u}_i$	Velocity vector of x, m/s
$\vec{u}_j$	Velocity vector of y, m/s
$\vec{v}$	Velocity vector of natural gas, m/s
x	The distance between the leak point and the upstream acoustic sensor, m
x_i	Value of i-axis in Cartesian Coordinates
x_j	Value of j-axis in Cartesian Coordinates
δ_{ij}	Unit tensor
$\delta(f)$	Dirac δ function
μ	Viscosity of gas, Pa s, μ is constant
ρ	The density of natural gas, kg/m^3
ρ_0	The undisturbed density of gas or the average density of gas, kg/m^3
ρ'	The fluctuations of gas density, kg/m^3
∇	Hamilton operator

(7) Cost is the money spent on investment of facilities and maintenance charge.

All evaluation indexes are considered as equivalent references, and the one of which the total choice number is the smallest is the best method. From Table 1, after comparative analysis it can be known that statistical method, distributed optical fiber method and acoustic method have better detection effect. But in fact there are still many problems unsolved for statistical method and the cost for distributed optical fiber method is highest. In view of these facts, acoustic method is promising and actual.

Studies on acoustic leak detection method have been focused on the propagation and signal processing of sound waves (Tolstoy, Horoshenkov, & Bin Ali, 2009; Yang, 2002), but the leak-acoustics generation mechanism is not considered, which is a key point influencing the leak-acoustics characteristics and signal recognition. And the detailed mechanism of leak-acoustics generation when leakages occur is still unsolved due to complex behavior of fluid (Außerlechner, Trommer, Angster, & Miklós, 2009; Braasch, 2008). This problem restricts the development of acoustic leak detection method.

In order to study the leak-acoustics generation mechanism, firstly the aero-acoustics generation mechanism should be investigated in theory to obtain the wave equation of sonic sources; then the leak-acoustics are simulated and compared with the data acquired through experiments to verify the accuracy of the simulation model.

2. Theoretical analysis

The leak-acoustics generation mechanism for natural gas pipelines is based on the aero-acoustics theory (Ma, 2004; Sun & Zhou, 1994), which focuses on fluid–fluid interaction and fluid–solid interaction. So the sonic sources distributed in the fluid field can be obtained from the basic equations of fluid mechanics.

The Navier–Stokes equation can be derived from the basic equations of fluid mechanics, which is referred to as N–S equation:

$$\rho\frac{dv}{dt} = \rho F - \nabla p + \mu\Delta v + \frac{\mu}{3}\nabla(\nabla\cdot v) \tag{1}$$

Then the Lighthill equation (Lighthill, 1952) is derived from N–S equation:

$$\frac{\partial^2\rho}{\partial t^2} - a_0^2\frac{\partial^2\rho}{\partial x_i^2} = \frac{\partial^2 T_{ij}}{\partial x_i x_j} \tag{2}$$

$$T_{ij} = \rho u_i u_j + \left[(p - p_0) - a_0^2(\rho - \rho_0)\right]\delta_{ij} \tag{3}$$

After Lighthill, in 1955, Curle (1955) used Kirchhoff method to promote Lighthill theory considering static solid boundary. Subsequently, in 1969, Ffowcs Williams & Hawkings (1969) used generalized function method to solve the acoustic problem induced by moving object in fluid and obtained Ffowcs Williams & Hawkings equation called FW–H equation.

$$\frac{\partial^2\rho'}{\partial t^2} - a_0^2\nabla^2\rho' = \frac{\partial}{\partial t}\left[\rho_0 u_i\frac{\partial f}{\partial x_i}\delta(f)\right] - \frac{\partial}{\partial x_i}\left[\left(p'\delta_{ij}\right)\frac{\partial f}{\partial x_i}\delta(f)\right] + \frac{\partial^2 T_{ij}}{\partial x_i\partial x_j} \tag{4}$$

Where the three parts in the right hand side can be regarded as three kinds of sonic sources: the monopole sonic source which is caused by surface acceleration or displacement distribution, the dipole sonic source which is caused by surface pressure fluctuations and the quadrupole sonic source which is caused by fluid turbulence.

According to the FW–H equation, the sonic sources generated when leakage occurs are composed of monopoles, dipoles and quadrupoles. The quadrupoles are caused by fluid turbulence when gas jets out of the leakage orifice. The dipoles are caused by gas–solid interaction between compressible gas and pipeline wall, valves and leakage orifice wall, etc. The monopoles are caused by fluid displacement distribution induced by pipeline wall rupture.

3. Simulation on leak-acoustics generation mechanism

In order to obtain the acoustic pressure perturbations generated by the monopoles, dipoles and quadrupoles, fluent software will be utilized for the simulation.