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A theoretical and experimental study on acoustic signals caused by leakage in buried gas-filled pipe

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ABSTRACT

In this study a theoretical analysis for non-linear vibrations of buried gas-filled pipes caused by leakage has been investigated. We considered the pipe as a cylindrical shell buried in an isotropic, homogeneous elastic medium. The standard form of the Donnell's non-linear shallow shell equation is used to model the free vibration of the pipe and the effects of surrounding medium on the pipe radial displacement is modeled by the potential function. The gas-structure interaction is analyzed by the Weaver-Unny model. By combination of these models and using the Galerkin method, the pipe wall radial displacement was obtained. A series of experiments were carried out on a steel pipe. The pipe was fitted with a continuous leak source positioned on the top of it and two ends of pipe were capped by plates. Two R15a sensors were mounted on the pipe. The pipe assembly was buried in a channel and sand was poured on it. The AE signals caused by leakage were recorded in large frequencies about 0–400 kHz. To study the accuracy of the present model, noises and unwanted signals were removed through the wavelet transform and then Fast Fourier Transform (FFT) was taken from theoretical and experimental results. The FFT results of theoretical model are compared with exciting experimental data and in all cases a good agreement is observed so that a percentage error less than 7% is resulted.

1. Introduction

When a material structure is damaged by an internal or external force or micro-structural changes occurred in the particle, it will be release elastic waves propagated through the material. This phenomenon named as acoustic emission (AE) is a robust and popular technique to evaluate and investigate damage propagation in the structures [1]. Pipeline leakage introduces high frequency sound waves which transmitted along the pipe wall with the form of elastic waves reflecting between the two surfaces of pipe and the tube wall surface limitation leads to guided waves in pipe [2]. When a solid body is excited by an impact or an abrupt displacement, it generates a dynamic problem, which is modeled by the corresponding movement equations. Escaping of fluid due to leakage in a pipe generates an acoustic emission signal which causes radial vibration [3]. A large number of studies on vibrations of circular cylindrical shells are available. Amabili [4] investigated large-amplitude vibrations of circular cylindrical shells with different boundary conditions and subjected to radial harmonic excitation in the spectral neighborhood of the lowest resonances. Zhang et al. [5] presented the numerical analysis of circular cylindrical shell by the local adaptive differential quadrature method which employed both localized interpolating basis functions and exterior grid points for boundary treatments. The governing equations of motion were formulated using the Goldenveizer–Novozhilov shell theory. Pellicano [6] analyzed the linear and non-linear vibrations of circular cylindrical shells. Sanders-Koiter theory was considered for shell modeling. Displacement fields were expanded by means of a double mixed series: harmonic functions for the circumferential variable; Chebyshev polynomials for the longitudinal variable. Then Lagrange equations are considered to obtain a system of ordinary differential equations from potential and kinetic energies and the virtual work of external forces. Davoodi et al. [7] applied a system of non-linear equations with 7 degrees of freedom to derive the pipe radial displacement caused by continuous leakage. They modeled the forced vibration of the pressurized pipe and checked the theoretical results with experimental. However when the pipe is buried in an elastic medium, little work is available in the literatures. Muggleton et al. [8] predicted the wave number of axisymmetric waves of buried pipes using Kennard's equations for low frequency and give some experiments. Liu et al. [9] investigated a theoretical analysis for the free vibration of simply supported buried pipes using the wave propagation approach. The vibrations of the pipe were examined by Fluggle shell equation.

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In this paper, a theoretical analysis for the forced vibration of buried gas-filled pipes caused by leakage is investigated and the characteristics of generated AE signals are analyzed. A theoretical model based on Donnell's non-linear theory, Weaver-Unny theory and potential function is employed and the motion equation of the pipe in radial direction has been derived by the Galerkin method and the effect of surrounding medium (sand) on the AE signals is surveyed. Experiments were carried out in a noisy condition with continuous leak source and pipe vibration was recorded using AE transducers. Comparing the theoretical and experimental results showed good agreements and high accuracy of the surveyed model.

2. Non-linear vibration of pipe

We considered the pipe of radius R, length L and wall thickness h as a cylindrical shell, constituted by an elastic, homogeneous and isotropic material with mass density of ρ surrounded by infinite elastic medium. The cylindrical coordinates system (x, θ, r) was used, where the axial, circumferential and radial coordinates are denoted by x, θ and r respectively. The values u, v and w represent the components of displacement at the shell surface in the axial, circumferential and radial directions respectively.

The simplified version of Donnell's non-linear shallow-shell equation is [10]:

$$D\nabla^4 w + ch\dot{w} + \rho h\ddot{w} = f - p + (1/R)(\partial^2 F/\partial x^2) + \frac{1}{R^2}\left(\frac{\partial^2 F}{\partial\theta^2}\frac{\partial^2 w}{\partial x^2} - 2\frac{\partial^2 F}{\partial x\partial\theta}\frac{\partial^2 w}{\partial x\partial\theta} + \frac{\partial^2 F}{\partial x^2}\frac{\partial^2 w}{\partial\theta^2}\right) \quad (1)$$

where D represents the flexural rigidity defined as $D = Eh^3/12(1 - \nu^2)$, c: damping factor, E: Youngś modulus, f: the force that is applied to the pipe surface caused by external medium and jet of leaking fluid, p: is the perturbation pressure which calculated by Weaver-Unny model [11], $\dot{w} = \partial w/\partial t$, $\ddot{w} = \partial^2 w/\partial t^2$ and F is in-plane stress function:

$$\frac{1}{Eh}\nabla^4 F = -\frac{1}{R}\frac{\partial^2 w}{\partial x^2} + \frac{1}{R^2}\left[\left(\frac{\partial^2 w}{\partial x\partial\theta}\right)^2 - \frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial\theta^2}\right] \quad (2)$$

In-plane stress equation is based on Donnell's non-linear theory. A partial difference equation (PDE) for in-plane stress function can be defined which has particular and homogeneous solutions:

$$F = F_h + F_p \quad (3)$$

where F_p and F_h denote particular and homogeneous solutions of in-plane stress function. More information in this matter can be obtained by [3].

The displacements u, v and w are expanded by using the eigenmodes of the simply supported shell [10]:

Table 1
Material and geometric parameters of steel pipe.

Material	R (mm)	h (mm)	ρ (kg/m^3)	L (m)	E (GPa)	ν	G (GPa)
ASTM (A 106/99)	130	6.4	7850	6	196	0.3	79

G and E are the shear modulus and the Young's modulus of the wall material respectively.
υ and ρ are the Poisson's ratio and density of the wall material respectively.

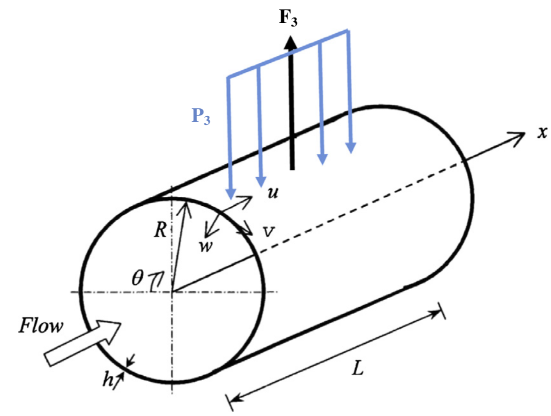

Fig. 1. Coordinate system of steel pipe.

$$\begin{aligned}
u(x,\theta,t) &= \sum_{m=1}^{M_1}\sum_{n=1}^{N}[u_{m,n,c}(t)\cos(n\theta) + u_{m,n,s}(t)\sin(n\theta)]\cos(\lambda_m x) + \sum_{m=1}^{M_2} u_{m,0}(t)\cos(k_m x) \\
v(x,\theta,t) &= \sum_{m=1}^{M_1}\sum_{n=1}^{N}[v_{m,n,c}(t)\sin(n\theta) + v_{m,n,s}(t)\cos(n\theta)]\sin(\lambda_m x) + \sum_{m=1}^{M_2} v_{m,0}(t)\sin(k_m x) \\
w(x,\theta,t) &= \sum_{m=1}^{M_1}\sum_{n=1}^{N}[w_{m,n,c}(t)\cos(n\theta) + w_{m,n,s}(t)\sin(n\theta)]\sin(\lambda_m x) + \sum_{m=1}^{M_2} w_{m,0}(t)\sin(k_m x)
\end{aligned} \quad (4)$$

n is the number of circumferential waves, m is the number of longitudinal half-waves and t is the time. $u_{m,n}(t)$, $v_{m,n}(t)$ and $w_{m,n}(t)$ are unknown functions of t. The additional subscript c or s indicates if the generalized coordinate is associated to a cos or sin function in θ except for v, for which the notation is reversed [10]. Axisymmetric modes ($n = 0$) having an even m value can be eliminated in the expansion, because they do not contribute to shell contraction. In fact, they present an integer number of longitudinal waves and therefore they have an average deflection equal to zero on the shell length. Specifically the following mode expansion is used [10]:

$$w(x,\theta,t) = \sum_{m=1}^{2}[A_{m,n}(t)\cos(n\theta) + B_{m,n}(t)\sin(n\theta)]\sin(\lambda_{(2m-1)}x) + \sum_{m=1}^{2} A_{(2m-1),0}(t)\sin(\lambda_{(2m-1)}x) \quad (5)$$

$\lambda_m = m\pi/L$ is the wave number and Eq. (5) satisfies the boundary conditions [10]:

$$w = 0, \quad M_x = -D\left[\frac{\partial^2 w}{\partial x^2} + \nu\frac{\partial^2 w}{R^2\partial\theta^2}\right] = 0 \quad \text{at} \quad x = 0, L \quad (6)$$

$$N_x = 0, \quad v = 0 \quad \text{at } x = 0, L \quad (7)$$

where M_x and N_x are the bending moment and the axial force per unit length [10].

The fluid is assumed to be incompressible and inviscid and the flow to be isentropic. Gravity effects, such as fluid weight are neglected. The irrotationality property is the condition for the