

ACOUSTIC EMISSIONS DUE TO LEAKAGE IN PIPELINES

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1 Introduction

Using acoustic waves in non-destructive testing of pipelines is a growing industry. The precision required necessitates the consideration of radiation loading. This paper outlines a mathematical analysis to obtain the acoustic emissions emanating from leaky pipeline by simulating the propagation of a sound wave in a fluid-filled, steel pipe. This work allows for three-dimensions distribution of the pressure and sound pressure level along the axial and circumferential directions which can facilitate a novel and very precise approach in detecting the pipeline leak using acoustic detection technology.

2 Methodology

2.1 Propagation of sound wave in a pipeline

Sound propagates by transmission of time-dependent pressure fluctuations due to leaky pipeline about the ambient pressure. The transfer of pressure fluctuation from fluid into an elastic medium such as steel pipeline is known as radiation loading. A portion of the acoustic waves will be absorbed and a portion will be reflected. This absorption and reflection must be included in a complete analysis, as must the attenuation of acoustic wave as it propagates through both the fluid and elastic structure. The equation of sound wave in a fluid is derived using continuity equation and Naviers stokes' equation for fluid flow:

$$\frac{\partial p}{\partial t} + \rho \operatorname{div} v + v \cdot \operatorname{grad} p = 0$$

$$\rho \left[\frac{\partial v}{\partial t} + (v \cdot \operatorname{grad}) v \right] = -\operatorname{grad} p + \eta \Delta v + \left(\zeta + \frac{1}{3} \eta \right) \operatorname{grad} \operatorname{div} v$$

where p, ρ, v, ζ are pressure, density, velocity and coefficients of viscosity

The polar co-ordinates (r, ϕ, z) are used considering the cylindrical geometry of pipeline. The sound wave equation for the perturbation of pressure p is given as

$$\nabla^2 p = \kappa \rho \frac{\partial^2 p}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}$$

where κ and c are bulk modulus and sound velocity in the fluid in pipeline.

The leakage in pipeline creates perturbation in pressure and hence the acoustic source is developed . To determine the acoustic pressure at any location r, ϕ, z in pipeline due to a simple acoustic source from a leakage in a pipeline at any arbitrary location at r_0, ϕ_0, z_0 in the pipeline wall(z being the pipeline axis) the following Green's function is used, which also satisfies the boundary condition at the pipeline wall given by the relation between the gradient of the acoustic pressure normal to the pipeline wall surface and the specific acoustic admittance β of the pipeline material[2]

$$\frac{\partial p}{\partial n} = ik\beta p \text{ where } k = \frac{\omega}{c}$$

The Green's function takes the form

$$g_{\omega}(r, \phi, z | r_0, \phi_0, z_0) = \frac{i}{\pi b^2} \sum_{m,n} \frac{\Psi_{m,n}(r, \phi) \Psi_{m,n}(r_0, \phi_0)}{\Lambda_{m,n} k_{m,n,z}} \exp(ik|z - z_0|)$$

where $\Psi_{m,n}(r, \phi) \Psi_{m,n}(r_0, \phi_0)$ are orthogonal functions

$$\Lambda_{m,n} = \frac{1}{\varepsilon_m} \left[1 - \frac{m^2 + (\beta kb)^2}{(\pi q_{m,n,r})^2} \right] J_m^2(\pi q_{m,n,r})$$

$\varepsilon_m = 1$ when $m = 0$ and $\varepsilon_m = 2$ when $m > 0$.

$q_{m,n,r}$ is eigen value for radial wave number for (m,n) th mode shape

$k_{m,n,z}$ is axial wave number for (m,n) th mode shape

$J_m(\pi q_{m,n,r})$ Bessel function m_n order

b = inside diameter of the pipeline

Using the Green's function, the acoustic pressure distribution p can be determined by simulating the acoustic source due to leakage as quadrupole acoustic source[3].

2.2 Absorption and attenuation of acoustic energy

When a sound wave is incident on the pipeline wall, some of the energy is reflected and some is absorbed by the surface. These losses of the sound energy are in addition to the internal energy losses of the sound energy due to viscosity and heat conduction. The coefficient of viscosity is modified as per Kirchoff's equation to account for effects of viscosity and heat conduction which in turn affects the sound velocity in the fluid (specifically for gases).

$$\mu_c = \mu \left\{ 1 + \left(\gamma^{1/2} - \frac{1}{\gamma^{1/2}} \right) \left(\frac{K}{\mu C_p} \right)^{1/2} \right\}$$

additionally the Korteweg-Lamb correction[1] is applied to calculate the modified sound velocity in the pipeline fluid.

$$c_c / c = \left[1 + \left(\frac{2b\rho c^2}{h\rho_p c_p} \right) \right]^{-1/2}$$

To account for losses due to reflection of acoustic waves from the pipeline wall the absorption coefficient is calculated as if the surface impedance is the function of frequency[2].

$$\alpha = \frac{1}{2\rho c I} \int_0^{2\pi} d\phi \int_0^{\pi} \alpha(\theta) |p|^2 \cos \theta \sin \theta d\theta$$

θ = Angle of incident; ϕ = Polar angle for pipeline geometry

$$\alpha(\theta) = 1 - |C_r|^2; C_r = \frac{z(\omega) \cos \theta - \rho c}{z(\omega) \cos \theta + \rho c}; z(\omega) = \text{Impedance}$$

I = Incident Power per unit area

$$= \frac{1}{2\rho c} \int_0^{2\pi} d\phi \int_0^{\pi} |p|^2 \cos \theta \sin \theta d\theta$$

ANSYS was used to calculate the natural frequencies for the continuous simply-supported pipeline which was then incorporated to calculate impedance for the pipeline.

2.3 Acoustic wave transmission thru the pipeline wall

The radiation of sound from an infinite elastic cylindrical shell excited by an internal sound source are analysed by coupled equations of motion. The Donnell's formulation is used [1] which is based on the assumption that the expression for the change in curvature and the twist of the cylindrical pipeline are the same as those of the flat plate and that the effect of the transverse shearing-stress resultant

on the equilibrium of the forces in the circumferential direction is negligible. The radiated acoustic pressure from the surface of the pipeline is given by [5][1]:

$$P_{\text{radiated}} = (p/a)(\rho_f/\rho_s)\Omega^2(h/r)^{-1} \sum_{m=0}^{\infty} \epsilon_m \dots$$

$$\int_{-\infty}^{\infty} [J_m(k_{m,n,r}r)/J'_m(k_{m,n,r}r)k_{m,n,r}r] [H_m(k_{m,n,r}r)/H'_m(k_{m,n,r}r)k_{m,n,r}r] I_{33} \dots$$

$$\times \exp[i(k_{m,n,z}z)(z/r)] h(k_{m,n,z}r)$$

where: $J_m(k_{m,n,r}r)/J'_m(k_{m,n,r}r)k_{m,n,r}r = \frac{z}{\rho c k b}$ on inside of pipeline

$H_m(k_{m,n,r}r)/H'_m(k_{m,n,r}r)k_{m,n,r}r = \frac{z}{\rho_f c k a}$ on outside of pipeline

(a is mean radius of the pipeline)

h = pipeline wall thickness;

p = Calculated acoustic pressure after accounting for losses

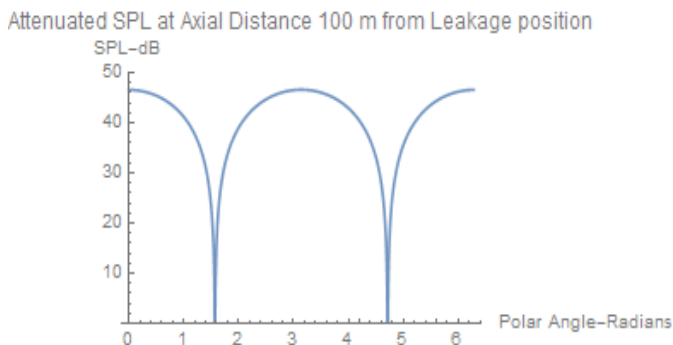
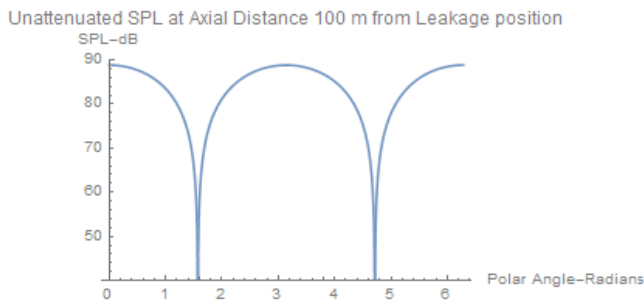
I_{33} = coefficient calculated from equations of motion from Donnell's formulation for radial displacements

Using the above described methodology, the complete profile of acoustic pressure inside the pipeline and outside the pipeline due to leakage, can be plotted as shown in the following section.

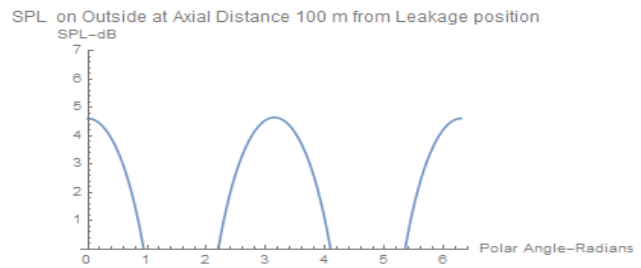
3 Results

3.1 Acoustic pressure distribution inside the pipeline wall (Mode shape m=0,n=1)

Data used for the acoustic pressure analysis is for 16", carbon steel pipeline. Pipeline wall thickness is 9.525 mm. Unattenuated and attenuated acoustic pressure distributions on the inside of the pipeline at a distance of 100 m from one end are as shown below. The driving frequency is 5000 Hz. The size of leakage hole is 2 mm dia and rate of leakage is 10 litres per minute:



3.2 Acoustic pressure distribution outside the pipeline wall (Mode shape m=0,n=1)



Discussions

On the inside radius of the pipe, a significant pressure level attenuation – approximately a 48% reduction in sound pressure level(SPL) from the unattenuated case – shows the internal energy losses due to Korteweg-Lamb correction at the boundary and the internal reflection from the pipeline inside wall surface. At the outside radius of the pipe, the significant pressure losses – 90% reduction in SPL in comparison to the attenuated inside radius – stem from the radiation of the pressure wave from the surroundings. At this surface, the attenuation of the pressure wave is much more rapid than at the inside radius, which is reflected in the lower SPL seen at the outside radius.

4 Conclusion

The significance of the results shown above may not be readily apparent, but they show that the method developed in this paper is powerful and versatile. Using this method, given an initial source frequency, the SPL can be accurately calculated at any distance from this source given a fluid and an elastic pipe. This includes a distance outside the pipe, away from its surface. The effects of the fluid type, fluid velocity and profile, pipe material and thickness, and surrounding medium can all be tested and compared efficiently using this method. The different sensitivities of stiffness-controlled systems may also be easily studied using this method.

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