Journal of Fluids and Structures 69 (2017) 252–264

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Experimental and numerical analysis of directional added mass effects in partially liquid-filled horizontal pipes

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ARTICLE INFO

Keywords:
Fluid–structure interaction
Liquid-filled pipe
Experimental modal analysis
FEM acoustic analysis
Added mass coefficient

ABSTRACT

The change of pipe natural frequencies due to added mass effects has been investigated in two cylindrical horizontal pipes from empty to completely water filled cases with various intermediate partially-filled conditions. The added mass coefficients of the three first vertical and horizontal modes of vibration have been determined with both experimental modal analysis and finite element analysis (FEA) acoustic-structural numerical simulations, which showed good agreement. The vertical and horizontal added mass coefficients present different behaviors as a function of the water level. Moreover, the pipe cross sectional dimensions determine the magnitude of these effects. For generalization to any pipe size, dependency of the directional added mass coefficients with new vertical and horizontal added mass estimators has been found. These estimators can be used in practical situations with horizontally mounted cylindrical pipes as a reference to predict and quantify air content.

1. Introduction

The interest in horizontal pipeline flow of air-water mixtures started many years ago, as shown by the experimental work of Govier and Omer (1962) in 1962 who compared various methods to correlate the pressure drop with the air-water ratio. As clearly exposed by Escarameia (2007), the presence of air in pipe systems can result in problems such as carrying capacity drop, flow disruption and reduced pump efficiency. Consequently, in large piping systems, considerable costs are incurred to remove the accumulated air due to dissolved gas or entrapment at pumps or air valves. In pressurized piping systems where optimal air release systems are too expensive or where the operation requirements do not permit to regularly apply hydraulic removal actions, a method for detection and diagnosis of gas pockets is of interest to avoid operation failure or undesirable discharge levels. For example, Lubbers and Clemens (2007) have carried out several experiments to detect gas problems using dynamic system response analysis. Such nondestructive methods are obviously helpful to overcome potential problems by applying remedial measures in advance before any unexpected catastrophic failure.

Pipe systems conveying fluid are Fluid-Structure Interaction (FSI) systems that have been modeled and simulated with different procedures, such as the ones proposed by Lavooij and Tijsseling (1991) for instance. A broad overview of the literature pertaining to the dynamic analysis of fluid-filled systems considering FSI are presented by Li et al. (2015).

In the present work, it is intended to investigate the suitability of detecting and quantifying the presence of gas pockets in circular cylindrical horizontal shells by assuming that their natural frequencies will change relative to the fully liquid-filled condition due to

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.01.001
Received 6 June 2016; Received in revised form 15 November 2016; Accepted 3 January 2017

added mass effects. The presence of an incompressible, inviscid liquid partially filling a clamped-free pipe was theoretically, numerically and experimentally proved to change its modal properties as a function of liquid level by Chiba et al. (1984a, 1984b, 1985). Amabili and Dalpiaz (1995) and Amabili (1996, 1997a, 1999) from 1995 to 1999 carried out extensive theoretical and experimental studies to obtain exact solutions for the free vibration problems of circular cylindrical tanks and pipes from partially liquid-filled conditions to completely filled and partially immersed in dense fluids. As a result, the natural frequencies and the mode shapes were theoretically found as a function of the water level and validated through comparison with results of experimental modal analyses. A different numerical approach was proposed by Chen and Ding (1999), Mazúch et al. (1996) and Ergin and Temarel (2002), who used the finite element method (FEM). In particular, the latter authors calculated the FSI effects in terms of generalized added masses.

In particular, the natural frequencies of two horizontally free mounted pipes with nominal diameters of DN32 and DN50 (ISO) will be calculated as a function of the water filling level. Experimental modal analyses and numerical simulations results will be compared and validated. Then, frequency ratios and added mass coefficients will be analyzed and discussed for vertical and horizontal directions. And finally, two mathematical expressions to estimate the added mass effects as a function of water level will be proposed that can be used in practical situations to predict the presence of large air pockets in pipes.

2. Theoretical approach

Unlike simple structures such as beams, the mathematical approach to study the dynamic behavior of cylindrical shells is far more complex. Most of the published work by Amabili (1997b) and Amabili et al. (2001) focus on the simply supported case because this boundary condition applied to both ends of the shell greatly simplifies the computational effort. However, in the present work, the authors have focused on a free-free condition shell which has received much less attention but could be considered as an ideally isolated basic case.

In particular, Warburton (1965) applied the generalized approach to the free-free condition shell, which was also reproduced by Blevins (1979). For that, the characteristic equation in matrix form, **A**, of an empty cylindrical shell is expressed with Eqs. (1)–(4):

$$\mathbf{A}=\begin{bmatrix} (A_j^2+\frac{1}{2}(1+k)(1-\nu)i^2\alpha_2)-\alpha_2\Omega^2 & A_j(-\nu i\alpha_1-\frac{1}{2}(1-\nu)i\alpha_2) & A_j(-\nu\alpha_1+k(-A_j^2+\frac{1}{2}(1-\nu)i^2\alpha_2)) \\ A_j(-\nu i\alpha_1-\frac{1}{2}(1-\nu)i\alpha_2) & (i^2+\frac{1}{2}(1+3k)(1-\nu)A_j^2\alpha_2)-\Omega^2 & i+kiA_j^2(\nu\alpha_1+\frac{3}{2}(1-\nu)\alpha_2) \\ A_j(-\nu\alpha_1+k(-A_j^2+\frac{1}{2}(1-\nu)i^2\alpha_2)) & i+kiA_j^2(\nu\alpha_1+\frac{3}{2}(1-\nu)\alpha_2) & (1+k(A_j^4+(i^2-1)^2+2\nu i^2A_j^2\alpha_1+2(1-\nu)i^2A_j^2\alpha_2))-\Omega^2 \end{bmatrix} \tag{1}$$

$$A_j=\gamma_J\frac{R_s}{L_s} \tag{2}$$

$$k=\frac{e^2}{12R_s^2} \tag{3}$$

$$\Omega^2=\omega^2R_s^2\left(\frac{\rho(1-\nu^2)}{E}\right) \tag{4}$$

Where γ_J is the equivalent beam frequency parameter, R_s is the shell radius, L_s is the axial length, e is the wall thickness, E is the Young's modulus, ν is the Poisson's ratio, ρ is the density, i and j are the number of circumferential waves and longitudinal half-waves, respectively, α_1 and α_2 are parameters that depend on the boundary conditions and ω is the circumferential natural frequency. So, the natural frequencies can be obtained by solving the eigenvalue equation which can be expressed with Eq. (5):

$$det(\mathbf{A})=0 \tag{5}$$

To consider the effect of a fluid on the natural frequencies of a fully filled simply supported cylindrical shell, Amabili et al. (2001) used the factor χ expressed in Eq. (6).

$$\chi=\frac{1}{\rho}\frac{I_{i+1}\left(\frac{j\pi R_s}{L_s}\right)}{I'_{i+1}\left(\frac{j\pi R_s}{L_s}\right)}\left(\rho+\frac{\rho_f L_s}{j\pi R_s}\right) \tag{6}$$

Where I_i is the modified Bessel function of order I and I'_i its derivative and ρ_f is the fluid density.

Unfortunately, the use of χ in **A** does not solve the natural frequencies of the free-free fully filled shell. Moreover, partially filled cases are even more complex to study analytically.

Consequently, the current work intends to propose alternative empirical correlations which could give reasonable approximations with very low calculation effort. Specifically, the authors will focus on the first three natural frequencies of “beam-like” bending mode shapes which, mathematically, can be expressed by Eq. (7):