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Vibration response of a pipe subjected to two-phase flow: Analytical formulations and experiments

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HIGHLIGHTS

- Analytical formulations for two-phase flow-induced vibration (2-FIV) are presented.
- Standard deviation of acceleration pipe response is a function of the square of shear velocity.
- Peak frequency is correlated to hydrodynamic mass and consequently to void fraction.
- Dynamic pipe response increases with increasing mixture velocity and void fraction.
- Hydrodynamic mass in 2-FIV in horizontal pipe is proportional to mixture density.

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ABSTRACT

This paper treats the two-phase flow-induced vibration in pipes. A broad range of two-phase flow conditions, including bubbly, dispersed and slug flow, were tested in a clamped-clamped straight horizontal pipe. The vibration response of both transversal directions for two span lengths was measured. From experimental results, an in-depth discussion on the nature of the flow excitation and flow-parameters influence is presented. The hydrodynamic mass parameter is also studied. Experimental results suggest that it is proportional to mixture density. On the other hand, two analytical formulations were developed and tested against experimental results. One formulation predicts the quadratic trend between standard deviation of acceleration and shear velocity found in experiments. The other formulation indicates that the peak-frequency of vibration response depends strongly on void fraction. It provides accurate predictions of peak-frequency, predicting 97.6% of the data within ±10% error bands.

1. Introduction

Flow-induced vibration is a common phenomenon in industry. The flow generates dynamic fluid forces which excites the structure inducing mechanical vibrations. The phenomenon has been studied extensively over the last four decades, mainly for nuclear industry applications (*e.g.* Fujita, 1990; Païdoussis, 2006; Pettigrew et al., 1998; Weaver et al., 2000). To date, the phenomenon of structural vibration induced by single-phase flow (FIV) is reasonably well understood. Researchers have aimed to reach that same level of understanding for vibrations due to two-phase flow. This is a challenge considering that it depends on the full understanding of the two-phase flow mechanisms, which still is an open topic.

On account of the emphasis of research on nuclear industry, where both axial and cross flows are predominant, the available information on flow-induced vibration subject to two-phase pipe flow is scanty (Chen, 1991; Ortiz-Vidal and Rodriguez, 2011; Pettigrew et al., 1998). Experimental studies noticed influence of two-phase flow parameters such as, mixture velocity, void fraction and flow-pattern on the structural response of the pipe system. For example, vibration response increases with increasing mixture velocity and homogeneous void fraction. It also depends on flow-pattern (Geng et al., 2012; Ortiz-Vidal et al., 2013; Zhang and Xu, 2010). The characteristics of bubbly flows can change due to the level of flow-induced vibration and as a function of liquid superficial velocity; however, these changes are not big enough to alter the flow pattern (Hibiki and Ishii, 1998). Despite the mentioned findings, a comprehensive and deeper discussion on the effect of two-phase flow parameters on vibration response is in order. The

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Nomenclature

A	cross-sectional inside pipe area, [m^2]
C	damping coefficient, [N·s/m]
d, D	internal and external diameters, [m]
EI	rigidity, [N·m^2]
J, J_*	(mixture) velocity, shear velocity, [m/s]
J_i	joint acceptance [adm]
L_{span}	length between clamps, [m]
m	linear mass density, [kg/m]
P	pressure, [Pa]
p'	pressure fluctuation, [Pa]
Q	volumetric flow rate, [m^3/s]
$y(x,t)$	transversal displacement of the pipe [m]
STD, PSD	standard deviation and power spectral density
r	radius [m]
V	velocity [m/s]
v'	velocity fluctuation [m/s]
x	quality [adm]
α	void fraction [adm]
β	homogeneous void fraction [adm]
ζ_T, ζ_s, ζ_{tp}	total, structural and two-phase damping components [%]
μ	viscosity [Pa·s]
ρ	density [kg/m^3]
$T_{k,w}$	wall shear stress of k-phase
τ_{wall}, τ_{lam}, τ_{turb}	wall, laminar and turbulent shear stress [N]
ω_i, ω_{peak}, ω_{air}	natural (for ith mode), resonance-peak and in-air frequencies [Hz]
$\phi(x)$, $\psi(x)$	mode shapes of the pipe and the pressure field

Subscripts

acc	acceleration
G, L	gas (air), liquid (water)
h	hydrodynamic
H	homogeneous
k	k-phase
L_{span}	length between clamps [m]
M	mixture
p	pipe

nature of flow excitation and the effect of flow patterns, specially slug-flow, and flow-pattern transition on vibration response should be analyzed.

Dynamic response of a pipe subjected to two-phase flow can be represented by damping, hydrodynamic mass and excitation mechanisms (Fujita, 1990; Pettigrew and Taylor, 1994). These dynamics parameters are also related to two-phase flow parameters. Significant research efforts on the study of damping have been spent in recent years (Béguin et al., 2009; Charreton et al., 2014; Gravelle et al., 2007). Results indicate that both structural and two-phase damping components are relevant in structural vibration induced by two-phase flow (2-FIV) in pipes. Furthermore, the latter has a viscous nature (velocity dependent) and is highly dependent on void fraction. Hydrodynamic mass in two-phase pipe flow, on the other hand, has not received much attention. No report on any experimental study has been found in the literature. In the case of excitation mechanisms, both turbulence and two-phase flow are the most important mechanisms in two-phase pipe flow (Pettigrew and Taylor, 1994; Riverin and Pettigrew, 2007). An analytical deduction has been reported in the literature to describe a relationship between vibration response and flow rate based on the mechanism of turbulence (Evans et al., 2004). No other formulation on vibration response including excitation mechanism has been found in the open literature.

In this paper, flow-induced vibration subject to two-phase pipe flow is investigated. Experiments in a broad range of two-phase flow conditions, including bubbly, slug and dispersed flow, in two span lengths of a clamped-clamped straight horizontal pipe are carried out. We present an in-depth discussion on 2-FIV vibration response from these experiments; *e.g.* the effects of flow-pattern and hydrodynamic mass are presented. In addition, two analytical formulations are developed and tested. One relates the vibration response to shear velocity based on the mechanical energy equation of the two-phase flow and random vibration concepts. The other formulation indicates the relationship between peak-frequency and void fraction.

2. Analytical approach

Fig. 1 represents a pipe subject to internal adiabatic two-phase flow, where the flow characteristics determine the governing vibration-excitation mechanisms, and consequently the vibration response $y(x,t)$. The turbulence and two-phase flow excitation mechanisms are the most relevant for both liquid and gas-liquid pipe flow (Pettigrew et al., 1998). Turbulence is associated to the presence of eddies of many sizes who decay to smaller ones, dissipating energy. The eddies in the region near the pipe wall generate random pressure fluctuations that forces it to vibrate (Blevins, 2001). In the case of two-phase flow, in addition to eddies, the instant reconfiguration of the phases induces perturbations on the flow. Depending of their nature, these perturbations can be another source of turbulence or can promote the emergence of a two-phase flow excitation mechanism. Thus, the relationship between the structural response and flow perturbations is evident.

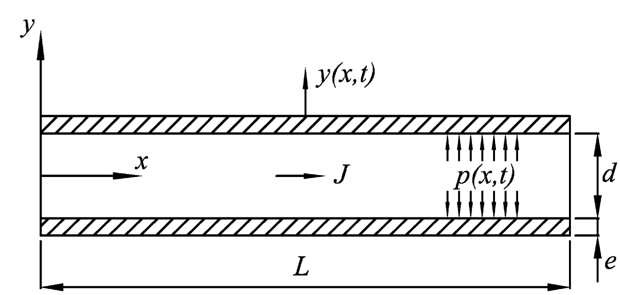

Fig. 1. Scheme of a pipe subjected to internal flow.

2.1. Relation between standard deviation of acceleration and shear velocity

The development of an analytical formulation of flow-induced vibration subjected to two-phase flow (2-FIV) in pipes has to do with the establishment of a relationship between flow and structure parameters. To date, exact mathematical deductions are not available, mainly because some topics, *e.g.* turbulence, two-phase flow and their interaction, are still in development. Here we analytically present a relationship between shear velocity and the standard deviation of acceleration of the pipe. This is done in two steps. First, the mechanical energy equation of the flow is used to relate pressure to shear velocity. Next, pressure and standard