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On the relationship between pipe accelerance and the void fraction of internal two-phase flow

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ABSTRACT

This work presents an experimental study on the forced vibration response of horizontal tubes subjected to internal gas–liquid *two-phase flow*. Vertical and horizontal polarizations of the flexural tube conveying mixtures of air and water are investigated. Firstly, the accelerance frequency response functions *FRFv* and *FRFh*, which represent the relationship between the acceleration in the vertical and horizontal axes and the corresponding forces measured in these directions, respectively, were obtained from different two-phase flow conditions in a wide frequency range (1–1600 Hz). Significant changes in the accelerance *FRF's* occur with void fraction. As expected, it was observed the increase in the natural frequencies of pipe and the increase of magnitude of the *FRF's* as a result of the reduction of the mass of liquid added to the tube with increasing void fraction of two-phase flow. The *differences* b*etween* the *FRFv* and the *FRFh* due to the asymmetry of the horizontal two-phase flow are investigated. Finally, the horizontal tube is harmonically excited at specific frequencies determined from the *FRF's*. Relationships between the pipe accelerance and the volumetric quality, as well as the relationships between the pipe accelerance and the void fraction of two-phase flow are obtained in the vertical and horizontal directions for different excitation frequencies. The results show that the pipe accelerance measured in the vertical and horizontal directions can be used to determine the void fraction and the volumetric quality of two-phase flow.

1. Introduction

Determination of the characteristics of internal two-phase flow based on the dynamic response of pipe has been the focus of a considerable number of studies. For instance, Geng et al. (2012) proposed an auxiliary measuring technology of wet gas flow based on the vibration signals of the pipe. Hua et al. (2010) proposed a noninvasive method to identify the wet-gas flow regime based on the flow-induced vibration. An experimental study on the measurement of air–water two-phase flow rate based on the pipe vibration was performed by Gama et al. (2009). A correlation between gas void fraction, absolute acoustic emission energy, and slug velocities in a two-phase air–water flow regime was developed by Al-lababidi et al. (2009) using an acoustic emission technique.

The knowledge of void fraction is important for the design and operation of two-phase flow systems. Calculation of pressure drop and heat transfer, as well the process control in nuclear and chemical plants depends on the prediction of

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void fraction. In this work, an experimental study was conducted to investigate the relationship between pipe accelerance and the void fraction of internal gas–liquid two-phase flow. The experimental investigation consisted of two steps. In the first step, vibration tests using impact and random excitation are performed in clamped–clamped horizontal tubes conveying air–water mixtures. The tube response is measured with accelerometers to obtain the accelerance frequency response functions (*FRF's*) of the tube. A *FRF* can be defined as a complex function that represents the relationship between the output and the input of a system as a function of frequency, and are commonly used to identify the characteristics of dynamic systems (see Ewins, 2009). Here, the system consists of a horizontal tube conveying mixtures of air and water, the input is the force applied to the tube and the output is the tube acceleration. The *FRF* given by the ratio of acceleration to the force is known as accelerance, and its reciprocal (force/acceleration), is the apparent mass of the system (see Ewins, 2009). The force applied to the tube and the acceleration measurements are in the vertical and horizontal directions normal to the tube axis, i.e. in the transverse directions. The pipe *FRF* is determined by processing the input (force) and output data (acceleration) using the same procedure for linear time-invariant systems. Despite the fact that the pipe conveying two-phase flow is actually a time-varying system, it will be demonstrated that the analysis of the averaged pipe *FRF* can provide information on the void fraction of two-phase flow using appropriate test conditions. Two accelerance *FRF's* are obtained from different two-phase flow conditions, namely *FRFv* and *FRFh*, which represent the relationship between the forces in the vertical and horizontal axes and the corresponding accelerations measured in these directions, respectively. In general we observed the increase of the pipe natural frequencies and the increase of magnitude of the accelerance *FRF's* with increasing void fraction of two-phase flow. Due to the asymmetry of the horizontal two-phase flow, significant differences are observed between the *FRFv* and the *FRFh*. These differences are mainly caused by the different amounts of liquid oscillating with the horizontal tube subjected to internal gas–liquid two-phase flow, when the tube vibrates in the vertical and horizontal directions. Similar behavior was observed in a previous work carried out with horizontal tubes partially filled with liquid (see Santisteban Hidalgo et al., 2017).

The variation of natural vibration frequency with void fraction of different systems has been reported in the literature. Charreton et al. (2015) stated that the natural frequency of their experimental apparatus is a good qualitative indicator of the actual void fraction in the test section. Escaler et al. (2017) investigated 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 added mass effects. Despite the fact that the changes of pipe natural frequencies can be a good indicator of void fraction, in this work we propose a different method to estimate the void fraction of two-phase flow. Due to the unsteady nature of the two-phase flow, the peaks of the *FRF* corresponding to the natural frequencies of the tube conveying mixtures of liquid and gas are not well-defined and cannot be determined precisely. This unsteadiness is caused by the spatial and temporal variation of the mixture density; resulting in the variation of effective mass and tube excitation (see Carlucci, 1980). The effective mass consists of a varying hydrodynamic mass, or added mass, plus the mass of the tube. We also noticed that the relative variation of the accelerance amplitude at certain frequencies is greater than the relative variation of the natural frequencies; consequently a better estimate of void fraction can be obtained from the amplitude variation of the accelerance *FRF*. In addition, the amplitude of accelerance at frequencies far from the resonance frequencies is less affected by the damping of two-phase flow.

In the second step of the experimental study, the tube is subjected to a harmonic excitation. Different excitation frequencies are chosen based on the analysis of the pipe *FRF* previously determined. These frequencies are distant from the natural frequencies, at which high variation of accelerance amplitude occurs due to changes in the void fraction. The harmonic force is applied to the tube using an electromagnetic actuator, and the pipe acceleration is measured in the vertical and transverse horizontal directions. Relationships between the tube accelerance and the volumetric quality of two-phase flow are obtained in the vertical and horizontal directions for the different excitation frequencies. The pipe accelerance in the horizontal direction as a function of volumetric quality showed little dependence on the mixture velocity of two-phase flow. The opposite was observed for the pipe accelerance in the vertical direction. This interesting phenomenon is explained later.

The void fraction is calculated using the correlation proposed by Woldesemayat and Ghajar (2006). The accelerance data in the vertical and horizontal directions as a function of void fraction showed little scatter. This is remarkable considering the different two-phase flow test conditions and regimes. The results showed that the pipe accelerance can be used as a good indicator of volumetric quality and void fraction of two-phase flow.

2. Basic definitions

The void fraction α in a two-phase gas–liquid flow may be defined as the fraction of total volume or the fraction of the total cross-sectional area that is occupied by the gas phase (see Charreton et al., 2015; Shohan, 2006):

$$\alpha = \frac{A_g}{A_g + A_l} \tag{1}$$

where, A_g and A_l are the pipe cross-sectional areas occupied by the gas and liquid phases respectively. The volumetric quality β is another parameter used to characterize the proportion of gas in a two-phase flow; it is defined as the ratio of volumetric flow rate of gas to the total volumetric flow rate:

$$\beta = \frac{Q_g}{Q_g + Q_l} \tag{2}$$