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FLOW-INDUCED VIBRATION DUE TO GAS-LIQUID PIPE FLOW: KNOWLEDGE EVOLUTION

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Abstract. *Gas-liquid flow is common in nuclear, refrigeration, gas and oil industries. Under certain circumstances, it can be a source of flow-induced vibration producing structural instabilities. This phenomenon should be avoided at all costs due to possible economic, environmental and even human losses. These factors have motivated important researches over the last three decades, mainly in the nuclear industry. This paper is an overview of theoretical and technological advances in this area, with special emphasis on flow-induced vibration due to two-phase pipe flow, gaps in knowledge and perspectives. Gas-liquid flow-induced vibration is described and classified. Also, the features of structural vibration and two-phase flow phenomena are presented. The influence of two-phase parameters, such as flow pattern, slip and void fraction, on generated vibration is presented. From the technical information available a classification of flow-induced vibration approaches is performed.*

Keywords*: pipe flow, two-phase flow, gas-liquid flow, structural vibration, flow-induced vibration (FIV)*

1. INTRODUCTION

Two-phase flow is common in nuclear, gas and oil industries, where gas-liquid mixtures are transported in piping systems. The fluids flow in different flow patterns, such as bubbly, slug, churn and annular, generating dynamic fluid forces which may induce structural vibration. Excessive excitation may lead to component failures, which must be avoided as they may produce heavy economic and even human and environmental losses. Therefore, the knowledge of flow-induced vibration (FIV) can have a significant impact on the proper design and operation of piping systems. These factors have motivated important researches over the last three decades (Chen, 1991; Païdoussis, 1998, 2005, 2008; Pettigrew and Taylor, 1994).

Historically, the FIV is a relatively new topic that embodies the fundamentals of fluids mechanics and structural vibration, among other topics. To date, most of FIV studies have been conducted for the nuclear industry, whose development has required information on Flow-Induced Vibration. Initially, significant research efforts were concentrated on the understanding of the FIV subjected to single-phase flow, which is now reasonably well understood. Currently, researches have aimed to reach that same level of understanding for flow-induced vibration due to two-phase flow (2-FIV). This is a challenge as it depends on the full understanding of the two-phase flow mechanisms, which still is an open topic (Chen, 1991; Liu and Gorman, 1996a, 1996b; Païdoussis, 2005, 2006, 2008; Pettigrew *et al.*, 1998).

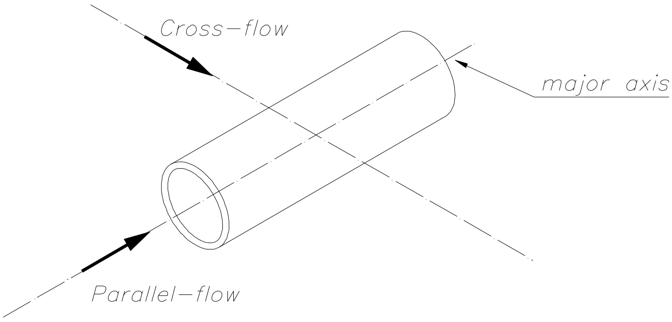


Figure 1. Types of 2-FIV classified by direction of flow

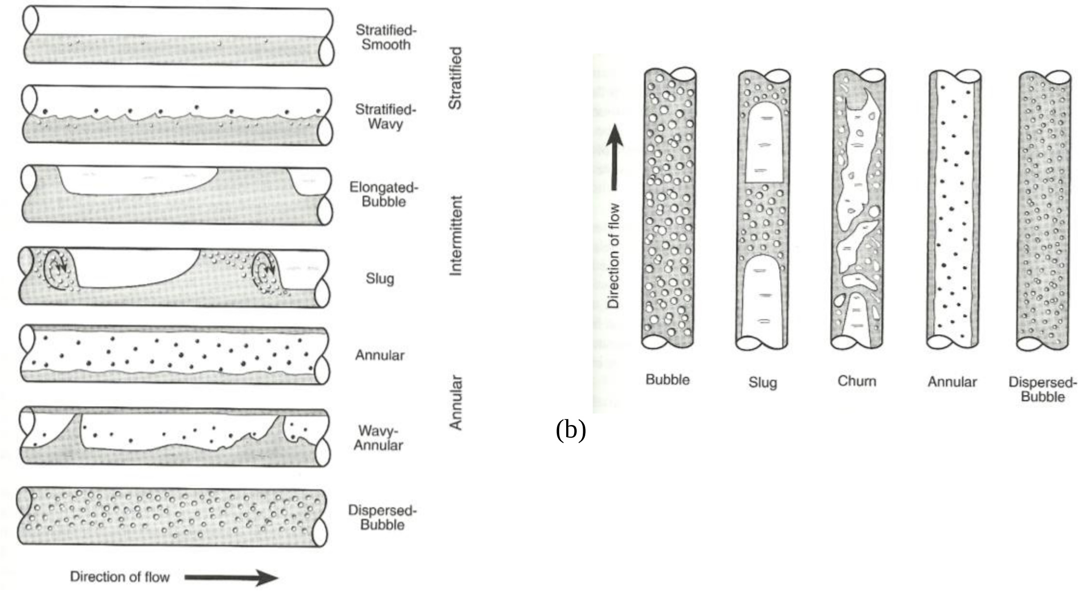
The 2-FIV, classified by direction of flow with respect to the major axis of structural components, can be divided into cross-flow and parallel-flow, in which the flow direction is perpendicular and parallel to the structural axis, respectively, as shown in Fig. 1. Additionally, the 2-FIV subjected to parallel-flow can be subdivided into internal (or pipe) and external (or external-axial or simply axial) flow (Chen, 1991; Pettigrew and Taylor, 1994). Some heat exchanger equipments, such as condenser, evaporator, boiler, nuclear reactors, and oil off-shore risers operate simultaneously with cross and parallel-flow. Examples of cross and parallel-flow types are fuels flow in nuclear reactors and pipe flow, respectively. Most of the research work on 2-FIV area has been performed for cross-flow due to its application and importance in the nuclear industry. Problems with mechanical vibrations due to two-phase pipe flow (pipe-2-FIV) are very improbable in this industry because the velocities used are very low and there exists no problem of fluidelastic instabilities (Pettigrew *et al.*, 1998). The latter has determined a few studies on this topic. However, one should not forget the existence of important problems other than fluidelastic instabilities and also some industries where this pipe-2-FIV is excessive, as reported by Anton (2009).

This paper reports the knowledge evolution of mechanical vibrations due to two-phase pipe flow. A brief description of two-phase flow parameters and their influence on pipe-2-FIV is presented in Section 2. The features of the structural response subjected to two-phase flow are outlined in Section 3. Section 4 shows a classification of pipe-2-FIV approaches from the technical information available. Finally, the mainly conclusions and perspectives are presented in Section 5.

2. BRIEF DESCRIPTION OF TWO-PHASE FLOW

2.1. Gas-liquid flow-patterns

Two-phase gas-liquid pipe flow is the simultaneous flow of gas and liquid phases through the same pipe. Two-phase mixture flows in several configurations, called flow patterns. These patterns are mainly classified according to the morphological arrangement of the phases. In the past, on account of the subjectivity of visual observations to determine the flow patterns, there was a disagreement on their definition and classification. Currently, there are acceptable sets of flow patterns. For example, the traditional flow patterns for upward vertical pipe flow are bubble, slug, churn, annular and dispersed-bubble. For the case of horizontal and near-horizontal pipe flows the typical flow patterns are stratified-smooth, stratified-wavy, elongated-bubble, slug, annular, wavy-annular and dispersed-bubble (Shoham, 2006). The flow patterns above mentioned are shown in Fig. 2 and a broad definition of these patterns can be found in Shoham (2006).



(b)

(a)

Figure 2. Typical flow-patterns in two-phase pipe flow: (a) horizontal and near-horizontal pipe flow, (b) upward vertical pipe flow (from Shoham, 2006).

2.2. Gas-liquid flow definitions

Before proceeding with the explanation of two-phase flow it will be necessary to define some of the relevant terminologies (Rodriguez, 2008; Shoham, 2006; Wallis, 1969). Considering, both gas and liquid phases flow simultaneously through a pipe of area A (m^2), the gas, liquid and total injection flow rates (m^3/s) are Q_G, Q_L and Q, respectively. The fraction of injection flow rate of gas and liquid are, respectively,

$$C_L = \frac{Q_L}{Q_L + Q_G}\,, C_G = \frac{Q_G}{Q_L + Q_G} \tag{1}$$

The superficial velocities or volumetric fluxes of gas, J_G, and liquid, J_L, and the mixture velocity, J, are calculated from injection flow rates and pipe area, as follows

$$J_L = \frac{Q_L}{A},\ J_G = \frac{Q_G}{A},\ J = J_G + J_L = \frac{Q_G + Q_L}{A} = \frac{Q}{A} \tag{2}$$

The superficial velocity is a very important parameter because, among other things, it is always known and easily calculated. Nevertheless, it is not a real velocity as it considers that each phase flows alone in the pipe. In the two-phase flow it is assumed that each phase is contained in different parts of the pipe cross-sectional area. Thus, the real phase velocities or *in-situ* velocities are defined in function of flow rates and the area fraction for each phase occupies. The *in-situ* velocities of gas, v_G, and liquid, v_L, are defined as

$$v_L = \frac{Q_L}{A_L},\ v_G = \frac{Q_G}{A_G} \tag{3}$$

where A_G and A_L are the areas occupied for gas and liquid phases, respectively. The sum of these two areas equals the total pipe area (A). According to Eqs. (2) and (3), the *in-situ* velocity is always higher than the superficial velocity.

Whereas the two phases flow simultaneously through the pipe and each phase occupies a part of pipe, it is possible to define the liquid holdup (H_L) and the void fraction (α) parameters as the fraction of the volume element in a two-phase flow field occupied by the liquid and the gas-phase, respectively, where $H_L + \alpha = 1$. The space, r, and time, t, averages of the instantaneous liquid holdup and void fraction are given by

$$<\bar{H}_L> = \frac{\int\int H_L(r,t)\,dr\,dt}{\int dr \int dt},\ <\bar{\alpha}> = \frac{\int\int \alpha(r,t)\,dr\,dt}{\int dr \int dt} \tag{4}$$

Equation (4) is simplified to pipe flow assuming the cross-sectional average and volumetric average (Rodriguez, 2008; Shoham, 2006). Therefore, the *in-situ* volumetric fractions considering a local magnitude, *i.e.* for a differential-length of pipe (δL), are rewritten as

$$H_L = \frac{A_L\,\delta L}{A\delta L} = \frac{A_L}{A},\ \alpha = \frac{A_G}{A} \tag{5}$$

By substituting Eqs. (2)-(3) into Eq. (5) and rearranging yields, the *in-situ* velocities can be expressed as function of superficial velocities and in-situ volumetric fractions, as follows

$$v_L = \frac{J_L}{H_L} = \frac{J_L}{(1-\alpha)},\ v_G = \frac{J_G}{\alpha} \tag{6}$$

In gas-liquid flow the injection flow-rate fraction (C) and *in-situ* volumetric fraction of the phases are usually different. This phenomenon is caused by differences in density and viscosity between gas and liquid phases and is known as slip, s. The latter is defined by the rate between the ratio of injection flow-rate fractions and in-situ volumetric fraction, as follows

$$s = \frac{\dfrac{\alpha}{H_L}}{\dfrac{C_G}{C_L}} = \frac{v_L}{v_G} \tag{7}$$

Replacing Eq. (6) in Eq. (7), and from a known injection flow-rate, the direct relationship between the *in-situ* volumetric fraction and the slip is revealed. The slip velocity, v_{slip}, is defined as

$$v_{slip} = v_G - v_L \tag{8}$$

2.3. Gas-liquid flow maps

Gas-liquid flow maps are commonly used to show flow-pattern transitions. Fig. 3 shows one of the best known two-phase flow-pattern maps. The superficial velocities of liquid, J_L, and gas, J_G, are presented in the abscissa and ordinate axes of the flow map, respectively. This map can be used to determine the flow-pattern in horizontal two-phase pipe flow. Similar experimental maps are available for vertical and inclined two-phase flows. The theoretical prediction of boundaries between flow patterns has been attempted by many researchers, and the works of Taitel *et al.* (1980) and Taitel and Dukler (1976) are pioneers in flow-pattern predictions for upward vertical and horizontal pipe flow, respectively. These studies include mechanistic criteria and theories to predict the flow-pattern transitions; for example, the Kelvin-Helmholtz theory is used to predict the transition between stratified and slug-or-annular flow-patterns in two-phase horizontal flow. In 1987, Barnea (1987) reported a unified model to predict the flow-pattern transitions for the whole range of pipe inclinations. Later, important progress based on the studies mentioned above was made in order to refine the flow-pattern prediction models and estimate the void fraction and pressure drop for specific flow-patterns. For example, Zhao, 2005 reported a full study of recent mechanistic-based models for slug flow in vertical pipes. A selection of relevant papers is outlined in the References (Abdul-Majeed and Al-Mashat, 2000; Fabre and Line, 1992; Zhang *et al.*, 2003).

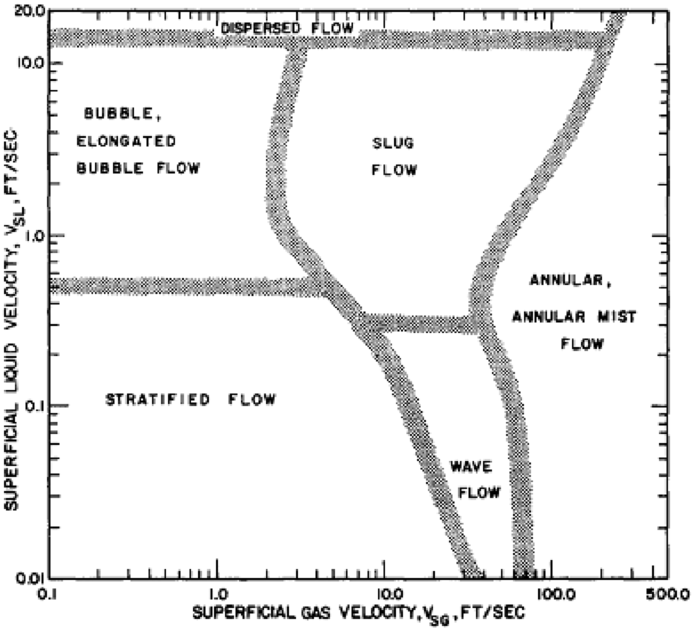


Figure 3. Flow-pattern map for gas-liquid horizontal flow proposed by Mandhane *et al.* (1974)

2.4. Influence of two-phase flow parameters on 2-FIV

The two-phase flow pattern, void fraction, slip and fluid compressibility parameters have important information on the 2-FIV phenomenon. These parameters take into account the flow fluctuations, density and pressure gradients, and are responsible for the complexity of 2-FIV phenomena (Chen, 1991; Pettigrew and Taylor, 1994). Fundamental experimental studies on 2-FIV have shown a strong influence of these parameters on the structural vibration response (Chen, 1991; Hibiki and Ishii, 1998; Hua *et al.*, 2010; Pettigrew and Taylor, 1994; Pettigrew *et al.*, 1998; Zhang *et al.*, 2008; Zhang and Xu, 2010).

Hibiki and Ishii (1998) performed an experimental work to test the influence of flow-pattern and void fraction on the vibration response. The results showed that the flow structure changes due to flow-induced vibration (FIV). For low superficial liquid velocity, FIV promotes coalescence of bubbles, however the increase of turbulence in the liquid phase (due to vibration response) may not be enough to breaking bubbles. On the other hand, for high superficial liquid velocity, FIV can be dominated by the liquid turbulence. The authors also analyzed the influence of FIV on void fraction, bubble size and slip. However, they said nothing about other flow-patterns and the value of two-phase flow parameters (e.g. gas and liquid velocities) from the vibration response. It should be mentioned that the work was directed to the study of heat transfer, whose variations in the flow structure can significantly change the heat transfer. Zhang and Xu (2010) also reported an experimental investigation on 2-FIV. They measured the FIV due to several void fractions and bubble sizes, finding that the vibration response rises by increasing the void fraction. These results show the vibration response is dependent mainly on the void fraction.

On account of the emphasis of research on nuclear industry, specifically 2-FIV for cross-flow, the available information on two-phase flow parameters for 2-FIV is quite scanty (Chen, 1991; Pettigrew and Taylor, 1994; Zhang *et al.*, 2008). There exist studies of bubbly and annular flow, but no study on slug flow, although it causes greater vibration amplitude because of its intermittent phenomenology.

3. STRUCTURAL REPONSE FEATURES

The dynamic fluid-structure interaction of a piping system subjected to two-phase flow can be represented as a damped system subjected to a set of external forces, as follows (Chen, 1991; Païdoussis, 1998; Weaver *et al.*, 2000)

$$[M]\{\ddot{Q}\}+[C]\{\dot{Q}\}+[K]\{Q\}=\{G\} \tag{9}$$

where [M], [C] and [K] are, respectively, the mass, damping and stiffness matrices, $\{Q\}$ is the vector of generalized structural displacement, and $\{G\}$ is the vector of the other excitation forces, including turbulence and acoustic noises; the overdot denotes differentiation with respect to time. Eq. (9) can be rewritten in a extended form showing the structural (s) and fluid (f) components of the system matrices,

$$[M_s+M_f]\{\ddot{Q}\}+[C_s+C_f]\{\dot{Q}\}+[K_s+K_f]\{Q\}=\{G\} \tag{10}$$

The major problem in 2-FIV is to know the mass [M_f], damping [C_f], stiffness [K_f] and excitation [G], due to two-phase flow, for various flow conditions. In general Eq. (10) is nonlinear, but the linearized equation is possible in most practical cases. The structural response may be periodic oscillations, random vibrations, or chaotic motions (Weaver et al., 2000). According to some authors, the structural response subjected to two-phase flow is represented by the hydrodynamic mass, damping and excitation mechanisms (Chen, 1991; Fujita, 1990; Pettigrew and Taylor, 1994).

3.1. Added mass and Damping

Pressure fluctuations due to two-phase flow produce hydrodynamic forces acting on the pipe systems. These forces are also caused by pressures from the two-phase mixture, occurring when the fluids must be displaced to accommodate the pipe motions. The two-phase mixture moving with the pipe has an important effect on the dynamics of the vibrating structure, particularly on its natural frequencies and damping characteristics. Hydrodynamic or added mass is related to natural frequency because in the coupled fluid-structure motion, the structure behaves as though an added mass of fluid were rigidly attached to and moving with it (Chen and Chung, 1976). Thus, added mass [M_f] is defined as the equivalent mass of fluid vibrating with a structure and is proportional to the fluid density and the structure volume. The added mass has been extensively studied for FIV caused by cross and axial-flow. For example, Carlucci (1980) and Carlucci and Brown (1983) studied the influence of void fraction on the added mass for 2-FIV in confined external-axial flow. The authors reported a decrease in the added mass with increasing void fraction. Pettigrew and Taylor (1994) obtained an empirical expression for the added mass in two-phase flow from Carlucci and Brown (1983) data. This expression embedded the effect of two-phase flow, such as void fraction and flow regime. Currently, several experimental and theoretical expressions are available for 2-FIV subject to cross and axial flows, but none to pipe flow (Chen, 1985; Païdoussis *et al.*, 2010; Païdoussis, 1998; Païdoussis, 2004). This lack of research could suggest that the added mass effect is irrelevant to pipe industrial applications. However, further studies on added mass for 2-FIV caused by internal axial flow are needed.

The damping is attributed to dissipative viscous losses and acoustic radiations. Damping absorbs mechanical energy, limiting the vibration response. Carlucci and Brown (1983) suggested that the total damping ratio, ζ_t, calculated for a typical two-phase flow should be of structural and fluid-related components, as follows

$$\zeta_t=\zeta_s+\zeta_v+\zeta_f+\zeta_{tp} \tag{11}$$

where ζ_s, ζ_v, ζ_f, ζ_{tp} are the structural, viscous, flow-dependent and two-phase damping, respectively. Structural damping ζ_s is dependent on the pipe's material and supports. The remaining terms on the right-side of Eq. (11) represent the total fluid damping. Experiments performed by Carlucci (1980) and Carlucci and Brown (1983) in a cylinder subjected to confined air-water axial flow show that the two-phase damping ζ_{tp} (or $\zeta_{2\varphi}$) is dominant over the other two fluid damping terms (see Fig. 4). Recently, Gravelle *et al.* (2007) reported experimental data of damping for two-phase gas-liquid vertical pipe flow. They found the viscous and flow-dependent damping in liquid flow to be very small and consequently reduced Eq. (12) to

$$\zeta_{2\varphi}=\zeta_t-\zeta_s \tag{12}$$

Gravelle *et al.* (2007) also found the two-phase damping $\zeta_{2\varphi}$ is critically dependent on void fraction, flow patterns and mixture velocity. With the help of Taitel *et al.* (1980) flow-patterns map, the authors showed that bubbly and dispersed bubble flow regimens present had higher damping. The two-phase damping increases with the void fraction until before the transition to a churn flow regime. At this moment, the two-phase damping ratio and void fraction reach maximum values at the same time and is possible that the gas medium may act as a source of damping. Based on their experimental data, Gravelle *et al.* (2007) proposed a analytical model to relate two-phase damping ratio and interface surface area. Later, Beguin *et al.* (2009) also studied the two-phase damping in 2-FIV subjected to pipe flow. They focused on the bubbly flow pattern correlating the two-phase damping ratio and the number of bubbles from a new proposed model.

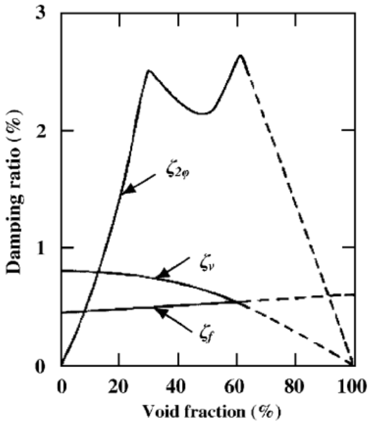


Figure 4. Components of fluid-related damping of a cylinder subjected to confined air-water axial flow (from Carlucci, 1980).

3.2. Vibration excitation mechanisms

Pettigrew *et al.* (1998) show that three vibration excitation mechanisms can be taken into account for mechanical vibrations due to two-phase pipe flow, namely fluidelastic instability, turbulence excitation and acoustic resonance. Although the previously mentioned mechanisms were reported for nuclear components, they can be considered for other applications since the physical principles are the same. Fluidelastic instabilities occur when two-phase fluid flowing through the pipe reaches a critical velocity, causing the structure to vibrate uncontrollably. This velocity is such that the energy absorbed from the fluid forces exceeds the energy dissipated by damping. According to Pettigrew *et al.* (1998), fluidelastic instabilities caused by two-phase pipe flow are usually not a problem for nuclear components because the flow velocities are normally much lower than the critical velocity, or in other words, the flexural rigidity of these components is relatively large. This reason has determined a few studies on this topic (e.g., Monette and Pettigrew, 2004). However, there are other applications, such as piping in chemical and petrochemical plants, in which the flow velocities are sufficiently high to cause structural instabilities. In this regard, Anton (2009) reported problems with excessive vibrations excitation due to two-phase hydrogen-oil flow in the hydro processing unit at Alberto Pasqualini Refinery - REFAP/SA. These problems could not be resolved with the technical information available. Thus, studies on fluidelastic instability excitation mechanism for two-phase pipe flow are needed.

Vibration excitation may be induced by turbulence and acoustic resonance (Blevins, 1990). Acoustic pressure pulsations originating from components of the piping system can promote an acoustic excitation frequency near that of the structure, causing large vibration amplitudes and even collapse of the system. On the other hand, turbulence-induced excitation generates random pressure fluctuations around the surface of components forcing them to vibrate. Recently, Sinha (2005) reported the possibility of using the vibration excitations generated in a natural gas pipeline for power generation. These vibration excitations, attributed to the turbulence-induced mechanism, can be converted into electrical power (~ a few mW). According to Pettigrew *et al.* (1998), turbulence-induced excitation is the principal vibration excitation mechanism in 2-FIV subjected to pipe flow. Despite the importance of this vibration excitation mechanism, it lacks studies about this and other mechanisms. Recently, Riverin and Pettigrew (2007) reported a new vibration excitation mechanism based on resonance phenomenon between periodic momentum flux fluctuations of two-phase flow and the first modes of the piping system.

4. FLOW-INDUCED VIBRATION APPROACHES

The literature indicates several approaches for 2-FIV problems subjected to pipe-flow. These can be classified into three categories: (i) coupled-systems, (ii) direct method and (iii) inverse method. Coupled-systems approach is a recursive problem, as shown by Fujita (1990): the fluid excitation generates vibration excitations in the structure and this vibrations can induce perturbations on two-phase flow, here it presents an interactive process. It is a classical problem of Fluid-Structure Interaction (FSI). However, the coupled-systems can also be considered non-recursive systems. The evaluation of fluidelastic instabilities is the most used analysis for coupled-systems. The structure and fluid equations are coupled and solved. Generally, these equations are nonlinear, but the linearized equations are possible for some applications from simple assumptions and empirical closure expressions. Thus, theoretical and empirical works are necessary to develop this topic. Païdoussis (1998) showed a full outline of fluidelastic instabilities due to flow-induced vibration in pipe flow. These instabilities occur when the mixture velocity reaches a critical velocity, causing excessive vibrations in the pipe. At this moment, the fluid excitation frequency is close to the structural characteristic frequency and it is suggested that the tube entered into resonance. Fluidelastic instabilities in coupled-systems subjected to pipe-flow have been less studied compared with those due to single-phase pipe-flow and single and two-phase cross-flow (Facchinetti *et al.*, 2004; Feenstra *et al.*, 2003; Gagnon and Païdoussis, 1994a, 1994b; Granger, 1990; Liu and Gorman, 1996a, 1996b; Mitra *et al.*, 2009). Monette and Pettigrew (2004) presented one of the few studies in fluidelastic instabilities on 2-FIV subjected to pipe flow. They carried out a series of experiments to investigate fluidelastic instabilities in a cantilever pipe. Monette and Pettigrew (2004) also developed a theoretical model to predict these instabilities from void fraction. Although the model included theoretical concepts and showed agreement with experimental data, it was developed for cantilever pipes and did not evaluate the influence of the two-phase flow pattern and the damping.

Direct method can be understood as a limited coupled-system approach. Structural response is studied from fluid excitation neglecting the perturbations of the structural response on two-phase flow and viceversa, i.e. the recursive effect is disregarded. This approach is used to study the influence of two-phase flow parameters on structural response such as vibration excitation types, generated forces, structural-support effects, and others. Generally, this approach is performed experimentally and when it is done theoretically the fluid and structural equations are uncoupled. In this regard, many recent studies have conducted experiments in pipe fittings finding relations between the flow fluctuations and the first vibration mode of the structure, and flow-induced forces and flow velocity. Also, models based on momentum exchange have been proposed to correlate two-phase flow parameters and structure forces generated (Belfroid *et al.*, 2010; Cargnelutti *et al.*, 2010; Riverin *et al.*, 2006; Riverin and Pettigrew, 2007; Tay and Thorpe, 2004). On the other hand, experiments and models for vertical and horizontal pipes have not been in the literature.

In the inverse-method approach, information on two-phase flow is obtained from structural response. It is a novel and useful approach, since the direct measurement of flow features is often difficult to access or even unknown. Significant research efforts have been concentrated on the inverse-method approach in the last one decade. Evans *et al.* (2004) studied the flow-induced vibration in pipe flow experimentally in order to obtain flow measurements from pipe response. This study was presented as a nonintrusive, low-cost, flowrate measurement technique. The tests were performed for single-phase flow whose main vibration excitation mechanism is turbulence. The vibrations were generated by pressure fluctuations and measured by an accelerometer attached to the surface of the pipe. The results showed a nearly quadratic relationship between the standard deviation of the accelerometer signal and the measured flowrate. Later, Gama *et al.* (2009) tried to extrapolate this technique for two-phase gas-liquid pipe flow. From their experimental results, they correlated the accelerometer response, specifically the root mean square (RMS), with the mixture velocity and void fraction. Despite the importance of the experimental data collected, the authors did not discuss the nature of the excitation mechanism and the influence of the two-phase flow-patterns was not considered either. Recently, Hua et al., 2010 developed a machine-learning algorithm, called MCSVM, capable of indentifing the gas-liquid flow-pattern for horizontal pipe from vibrations pipe response. The MCSVM algorithm is a variant of the Support Vector Machine (SVM) classifier. Experimental data were collected in order to train and test the algorithm. Hua *et al.* (2010) used a test section of 50 mm diameter and air and water as working fluids. Their results showed that the trained MCSVM could identify three horizontal flow patterns, namely stratify/stratify-wave-flow, annular/annular-mist-flow and slug flow, with an accuracy of 93.3%. Their work represents an important progress in the inverse-method approach, and the next step would be the determination of two-phase flowrates and void fraction from structural pipe response. Achieving this is a real challenge since some complex phenomena are involved. In this regard, phenomenological or analytical models have not been found in the technical literature for inverse-method approach. It should be mentioned for completeness that Granger and Perotin (1999) reported an inverse method for the identification of a distributed random excitation from the measurements of vibration response. The method is based on a modal model for the structure and a spatial orthonormal decomposition of the excitation field. In the second part of the work, the authors applied the developed inverse method to a flow-induced vibration problem subjected to cross-flow (Perotin and Granger, 1999). Granger and Perotin (1999)'s work can be very useful to the challenge mentioned.

5. CONCLUSIONS AND PERSPECTIVES

Although mechanical vibrations due to gas-liquid pipe flow are found in several industrial applications, they are not very well understood. The present paper outlined their knowledge evolution from the available technical literature. Firstly, the importance of the flow-induced vibrations caused by two-phase flow (2-FIV) was noticed. Then, a 2-FIV classification based on direction of flow was performed, showing that 2-FIV in internal flow (or pipe-2-FIV) is our research focus. The two-phase flow in pipes is briefly presented and is described the influence of its parameters, such as void fraction and flow-pattern, on generated vibration. The features of structural response and the approaches for flow-induced vibration are also commented on. While some progress has been accomplished to understand pipe-2-FIV, we have observed many knowledge gaps on this issue, specifically:

- Scarcity of experimental data and theoretical models of pipe-2-FIV for both horizontal and vertical flows.

- Absence of an in-depth theoretical description of interactive process between structure response and fluid excitations. For example, the possible perturbations of the structural response on two-phase flow parameters and viceversa.
- Lack of studies about added mass and as its relations with two-phase flow parameters on FIV phenomena.
- Scarcity of studies about damping, mainly two-phase damping, being its responsible for the energy dissipations of piping systems.
- Necessity of studies on the excitation mechanism of fluidelastic instability for pipe-2-FIV with velocities higher that found in nuclear industry.
- Necessity of evaluation of influence of all flow-patterns, capitally slug-flow since its intermittent nature causes vibration with large amplitudes. This missing information becomes a serious impediment to performing a pipe-2-FIV objective analysis.
- Lack of studies of nature of vibration excitation mechanisms.
- Necessity of direct and inverse-models of pipe-2-FIV considering the influence of two-phase flow and structural parameters, such as flow-patterns, void fraction, two-phase damping and structural-support. This information would be of great help to design stage.

6. ACKNOWLEDGEMENTS

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