Internal two-phase flow induced vibrations: A review

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Abstract: Flow-induced vibration (FIV) is a common phenomenon observed in internal flows and is frequently encountered in technical systems like process plants, nuclear plants, oil-piping or heat exchangers. Compared to single-phase flows, FIV is more difficult to predict and analyze for internal two-phase flows. As a result, experimental data and analysis tools related to two-phase flow are limited to specific aspects or conditions. Another problem is that for real-world applications, FIV analysis is applied to multi-structural components, which becomes complicated due to the size of the technical systems. Thus, experimental studies are usually realized first within the laboratory using a prototype of the original structure. Besides experimental investigations, Computational Fluid Dynamics (CFD) is increasingly adopted and already a prevalent tool for FIV assessment. However, further development in CFD models and methods is necessary in order to complement the experimental database. Additionally, CFD is useful for enhanced understanding of fundamental aspects of two-phase flows, and for gaining insights from situations where experiments are difficult or infeasible, such as in deep-sea bore-wells, sub-sea riser pipelines, and in nuclear installations. It is also known that there is a lack of sufficiently accurate empirical correlations for terms related to mass, momentum, and energy transfer across the phases for two-phase flows, and CFD can be useful in this respect. Furthermore, for estimating the accuracy of CFD models, comparisons with benchmark results for two-phase, internal, multi-structural flows are necessary. Unfortunately, the experimental database involving internal two-phase flows is very limited, and this is a bottleneck for the development of computational techniques. The following contribution presents a review of the research on FIV involving two-phase internal flows with relevance to multi-structural components. Methodological literature for two-phase flow measurements along with the latest applications are put forth. Problem areas of two-phase FIV systems have been brought out, and future avenues of research for two-phase, internal FIV are identified. The following specific areas of two-phase FIV are reviewed. Two-phase FIV in subsea risers and in pipeline riser systems is discussed.

PUBLIC INTEREST STATEMENT

Two-phase flows occur frequently in engineering such as in Nuclear Power Plants, Off-shore marine installations, chemical process plants. These installations are frequently affected by two-phase flow induced vibrations. These vibrations can become even more pernicious when they couple with the inherent structural vibration frequency. It is of utmost importance to study two-phase flows and flow-induced vibrations, their causes, and the methods of their control to avoid destructive damage due to two-phase flow induced vibrations. The review provides a detailed review of the various efforts, present and expected in future to address two-phase flow induced vibration phenomenon in multi-scale, multistructural component systems.
The slug flow regime is analyzed in particular due its predominant impact on two-phase FIV. Parameters affecting two-phase FIV along with two-phase correlations are discussed. Power Spectrum Density (PSD) and Fourier transform applications for two-phase FIV form another section. Latest research efforts involving the two-way interaction of fluid and structure are presented. Both numerical and experimental works have been reviewed. The bulk of the important works for two-phase FIV is experimental in nature. Numerical models and computational power have not been developed enough for simulating more complex, multistructural flows. They are limited to simple cases involving simplified computational models. Experimental efforts for large multistructural components involve the initial use of prototypes and can prove to be costly for fully developed industrial-scale rigs. However, experimentation currently holds an irreplaceable position in two-phase FIV studies.

Subjects: Mechanical Engineering; Mechanical Engineering Design; Structural Mechanical Engineering

Keywords: flow-induced vibration; two-phase; internal flow; multi-structural; multi-phase; fluid structure interaction

1. Introduction
Flow-induced vibration (FIV) in internal, two-phase, pipe flows arises due to the inherently fluctuating nature of two-phase flow. Two-phase FIV is frequently encountered in process plants, heat exchangers, nuclear and power plants, as well as energy equipment. It poses a major problem due to excessive and sometimes critical vibrations, which can cause loss in efficiency, reduction in component lifetime, unwanted noise, and minor or even major accidents. Blevins (1979, 1990) was the first to use and classify flow-induced vibrations. The vibrations induced by the two-phase flow can couple with structural vibrations. The resulting phenomenon, known as fluid-structure interaction (FSI), is more harmful compared to standalone FIV. Blevins (1990) showed that flow-induced vibrations can be fully described by the interaction of fluid and structure. The two-phase flow-generated forces cause the structure to vibrate, and, in turn, the structural vibration changes the flow, which further modifies the structural excitation response. This two-way interaction makes the analysis of two-phase FSI complex. Models for standalone, two-phase FIV and FIV-FSI coupling are needed to predict FIV over a wide range of conditions. Such models are also necessary for implementation in Computational Fluid Dynamics (CFD) codes for two-phase FIV-FSI analyses. CFD with FSI can be implemented using fundamental equations and advanced methods, such as Direct Numerical Simulations (DNS), wherein no turbulence model is used. However, such methods require very fine computational grids that usually require extremely high-end computational resources. Therefore, computational methods remain infeasible for most real-world, industrial, two-phase FIV scenarios. Furthermore, these models need to be validated with sufficient benchmarking experimental results before they are applied to advanced prototype or full-scale problems or in CFD simulations. Unfortunately, experimental database is still not available for various gas–liquid two-phase flow aspects, including large-diameter pipes, related regime transitions, interfacial area friction correlations, etc. As a result, such models are still under development.

In the area of two-phase instrumentation, there are ongoing advances that would increase the effectiveness of experimental results for two-phase flows in future.

In most multicomponent system applications, FIV-related problems are not taken into account during the design stage and these problems show up only when the system is run at full-scale operation. As mentioned earlier, the external indications of FIV are noise and system vibrations, and the more dangerous effects can be small- or large-scale accidents (L. Liu et al., 2021).
Industrial two-phase flows are usually classified as external and internal. External flows can be axial-flows and cross-flows. Figure 1 shows the two-phase flow classifications along with the primary sources of FIV. Localized fluctuations in mass, momentum and energy are the primary causes of FIV in two-phase flows, and these are noticed as void fraction and pressure fluctuations. Pressure fluctuations are further attributed to turbulence. Local mass fluctuations are caused due to the fluctuations in two-phase density caused by the large density difference between the phases (for example, in case of air-water two-phase flow, the density of water is 1000 kg/m$^3$, and the density of air is 1.2 kg/m$^3$). Momentum fluctuations occur due to a combination of mass fluctuations and velocity fluctuations. Velocity fluctuations are attributed to the difference in velocities of the individual phases. Phase changes such as in boiling and condensation cause energy fluctuations. Furthermore, external effects such as periodic/non-periodic mechanical/ machinery-induced vibration, external acoustic frequencies and structural response can be linked with the FIV to amplify the structural vibration and cause undesirable or dangerous consequences.

FIV can also be identified based on the two-phase flow “regime”. A description of two-phase flow regimes is provided in Section 1.1. Section 1.2 contains descriptions of various two-phase flow terminologies and flow regimes usually encountered in the literature. Flow regimes are found to differ with pipe orientation and flow conditions. Flow regime maps demarcate the various flow regimes for a given experimental condition and are usually plotted for varying superficial liquid and superficial gas velocities. The maps are plotted after extensive experimentation and differ in experimental conditions, such as flow geometry, pipe inclination, phase velocities, and phase change type (boiling/condensation).

As stated earlier, the flow regime has a distinct effect on FIV. In bubbly flows, a source of two-phase FIV is bubble-induced vibration. This is distinct from momentum-induced vibrations since momentum changes are not considered significant for bubbly flows. Similarly, momentum fluctuations have been found to be significant in the slug-flow regime. Slug flow occurs in internal two-phase flows, with a distinct separation between the phases, and liquid “slugs” alternate with gas-phase “Taylor bubbles” in the flow. As a consequence, the fluctuations in density are clear and
pronounced for the slug flow regime. Momentum fluctuations are found to be significant in the case of pipe bends, where the centrifugal force component adds to the force fluctuations.

Vibrations due to external flows such as axial-flow and cross-flow can be measured and quantified with good accuracy. Therefore, problems related to external two-phase flow are more easily identifiable (Kandasamy et al., 2016). However, experimentation and prediction in the case of internal two-phase FIV is not easy due to the lack of experimental database, models and non-intrusive instrumentation.

Plant component failures/disasters due to fatigue induced by FIV are found to occur in various situations. Al Asmi and Sebi (1998) identified the cause of vibration-induced fatigue failure of an impulse line connected to a crude oil pipeline header and to a pressure transmitter. Similarly, one of the causes of the fatigue failure of the weld joint of an afterburner fuel manifold of a jet engine was attributed to flow induced vibrations (Panda et al., 2013). More recently, Palsson et al. (2017) investigated the fatigue failure of a two-phase hydrocarbon conveying pipeline and identified the cause to be excessive vibrations in the structure. In order to avoid such disastrous events, the prediction of FIV phenomenon is of great importance, which can be done by measuring the relevant two-phase flow parameters during plant operation. For this purpose, a sufficiently well-developed experimental database is needed and this is an ongoing process.

Two-phase FIV is known to link/couple with external vibration sources, in particular, to the structural vibration response from the periodic or non-periodic excitation. However, in most experiments, the coupling of FIV with structural vibration has not been considered. In experimental tests, the test sections are usually clamped so that the vibration of the test section length is much higher compared to the FIV. Therefore, the possible linking of FIV and structural vibration is avoided. However, in practical situations, the piping structure is loosely supported to adjust for thermal expansions (Belfroid et al., 2016). A similar situation occurs for the case of sub-sea jumpers, where long sections of the riser are unsupported. Due to the longer pipe sections between the supports, the low frequency structural vibration can easily couple with FIV, which usually lie below 50–90 Hz. Most studies on sub-sea risers are computational due to the difficulties of real-

![Figure 2. Schematic of flow patterns in (a) vertical, and (b) horizontal two-phase co-current flow (Da Silva, 2008).](image-url)
world investigations or development of realistic flow loops for experimental tests. Hence, experimental studies for FSI or coupling of FIV to structural vibrations are hard to find. The FSI aspect should therefore be carefully investigated for every individual experimental setup.

A significant amount of research has been conducted in the past two decades concerning two-phase FIV in energy, power and process plants/systems (Anagnostopoulous, 2002; Carvalho et al., 2019; Cong et al., 2014; Weaver et al., 2000). However, much work remains to be done in various FIV-related areas. Some of these areas are mentioned as follows: (a) benchmark experiments investigating FIV and FSI problems; (b) development of validated models for a wide range of FIV-FSI conditions; (c) advancement in computational power for the implementation of FIV problems at the industrial scale, (d) development of predictive methods for FIV and related structural response; (e) preventive methods for FIV such as active and passive flow controls; and (f) decoupling FIV (mass, momentum, turbulence, energy, vortex-induced, swirl-induced) with external excitations (structural, acoustic, mechanical, rotary equipment).

The article is divided into the following sections. Sections 1.1 and 1.2 provide descriptions of two-phase flow regimes and two-phase flow terminologies, respectively. Section 2.1 presents the methodological literature on two-phase flow measurements, with Section 2.2 containing flow visualization methodologies. Section 2.3 contains the general two-phase internal flow literature with emphasis on FIV. Section 3 deals with FIV in the sub-sea riser system due to the typical challenges of such systems, and another subsection that details slug flow-related FIV. The slug flow regime is frequently associated with major FIV problems, with much of the literature devoted to the slug regime alone. Section 4 is divided into subsections investigating two-phase FIV parameters and their relation to FIV. Section 5 contains spectral analysis applications and results for two-phase FIV. In Section 6, literature relating to the coupling of FIV with structural excitation response, or FSI is presented. Force correlations are important for the prediction of FIV over a wide range of conditions. Force correlations from two-phase FIV experiments are discussed in Section 7.

1.1. Two-phase flow regimes

Flow regimes in internal two-phase flows are described in this section. The following reference materials provide in-depth treatments of multiphase flows. Brennen (2005) and Crowe (2006) discuss general multiphase treatments, while Azzopardi (2006) describes two-phase flows. Wörner (2003) provides an introduction to numerical modeling of multiphase flows, and Ghajar (2005) presents an excellent tutorial for two-phase flows without phase change.

Important two-phase flow regimes in vertically upward two-phase flows are shown in Figure 2 (a). The regimes are shown for a fixed liquid flow rate.

- **Bubbly flow** occurs at low gas flow rates. The gas phase is uniformly dispersed in the fluid, and the gas bubbles are of uniform size.
- **Slug flow** occurs for higher gas flow rates. Bubble collision and coalescence result in large sized “Taylor-Bubbles”. The liquid slugs alternate with Taylor bubbles and usually contain gas-phase bubbles.
- **Churn flow** occurs with increasing gas flow rate. The two-phase mixture is churned resulting in a breakdown of the Taylor-bubbles. The resulting gas bubbles are now irregular but large in shape. The liquid phase also contains small gas bubbles.
- **Annular flow** is observed with the occurrence of a liquid film at the pipe walls. The film is sustained due to a central core of gas moving at high velocity. Small liquid droplets are usually carried along with the gas phase.

Two-phase flow regimes in horizontal flows are shown in Figure 2. The effect of gravity causes the gas phase to be on top of the liquid phase.
• **Bubbly flow** is similar to its counterpart in vertical flows. Gas bubbles tend to rise to the upper portion of the pipe.

• **Plug flow** occurs due to frequent bubble collision and coalescence at higher gas flow rates. Bullet-shaped bubbles that are skewed towards the upper pipe region are seen.

• **Stratified flow** regime consists of a clearly demarcated region for the two phases, where the gas phase occupies the upper half of the pipe. Small ripples are prevalent at the interface of the two phases.

• **Wavy flow** occurs when the ripples in stratified flow are magnified into waves due to high kinetic energy of the gas phase.

• **Slug flow** is similar to slug flow as observed for vertical flows.

• **Annular flow** is similar to the annular flow regime observed for vertical, two-phase flows. However, the liquid film adhering to the pipe walls is not uniform as in the case of vertical flows, but is thinner near the upper walls, compared to the lower wall region.

### 1.2. Two-phase flow terminologies

Some of the important two-phase flow parameters as discussed by Brennen (2005) are mentioned. Terms that are frequently encountered in the literature are **Mass Flux**, **Volumetric Flux**, **Superficial Velocities**, **Volume Fraction** (alternatively termed as **Holdup**), **Void Fraction**, **Mass Fraction**, **Volumetric Quality**, **Mass Quality**, etc. The terms are defined considering a two-phase flow consisting of a liquid (L) and a gas (G).

The **Mass Flux** is defined as the mass flow rate of a phase per unit cross-sectional area occupied by that phase. It is denoted by \( G \), where \( G = \rho j \), and \( \rho \) is the phase (liquid or gas) density. The total mass flux is given as \( G = G_L + G_G \). Since \( G \) is the mass flow rate (in kg/s) divided by cross-sectional area (in m²), the SI units for \( G \) are kg m⁻² s⁻¹. The **Volumetric Flux** (or **Superficial Velocity**) for internal two-phase flow, is the volumetric flow rate per unit cross-sectional area of the pipe/conduit (compare this to the Mass Flux). It is denoted as \( j_L \) or \( j_G \) indicating the volumetric flux/superficial velocity of the liquid and gas phases, respectively. The measurement units for \( j \) are the same as the velocity, that is, m/s. The total **superficial velocity** is \( j = j_L + j_G \). The instantaneous, local velocities of the liquid and gas phases are denoted as \( u_L \) and \( u_G \). The relative velocity between the phases is \( u_L - u_G \). The **Volume Fraction** (Holdup) of a phase is the volume occupied by a phase to the total volume considered and is denoted by \( \alpha \). It follows that \( \alpha_L = 1 - \alpha_G \). The **Void Fraction** is the volume of the gas phase for unit volume of the pipe. From the above definitions, it follows that the **Volumetric Flux** (or **Superficial Velocity**) of a phase has the following relation to its volume fraction, and its velocity. For example, for the gas phase, \( j_G = \alpha_G u_G \). Therefore, the **superficial velocity** of a phase is the product of the phase volume fraction and the phase velocity. The **Mass Fraction**, \( x_L \), of the liquid phase is \( \rho_L \alpha_L / \rho \). The **Volumetric Quality** of a phase is defined as the ratio of the **Volumetric Flux** of the phase (L or G) to the total volumetric flux. For the liquid phase, the **Volumetric Quality** for the liquid phase would be \( j_L/j \). The **Mass Quality** (or **Quality**), for the Liquid phase, \( x_L \), is the ratio of the liquid mass flux to the total mass flux, \( G_L/G \), or \( \rho_L j_L / \rho j \). The **Drift Velocity**, or **Slip Velocity** of a phase is defined as the velocity of that phase in a frame of reference moving at a velocity equal to the total volumetric flux, \( j \). For example, the **Drift Velocity** for the Liquid phase \( (u_L) \) is written as \( u_L = u_L - j \).

### 2. General two-phase literature

This section is divided into three sub-sections. The first Sub-Section 2.1 presents the methodological literature for two-phase flow measurements. The second Sub-Section 2.2 presents literature relating to two-phase flow visualization. The last Sub-Section 2.3 has a general literature relating to two-phase flow and FIV.

#### 2.1. Two-phase flow measurement techniques

Flow-induced vibration measurements involve various methods for measuring important two-phase parameters, which provide information relating to FIV, either directly or indirectly. The direct
approach generally involves the measurement of transverse pipe vibrations in terms of vibration amplitude or displacement, acceleration, velocity, pressure fluctuations, and pipe frequency response due to excitation from FIV or external sources. Post-processing of these direct measurement signals in the form of fast form transforms (FFT), power spectrum density (PSD), and time-series analysis is needed to extract meaningful information related to FIV. The indirect method involves the measurement of relevant flow parameters, such as two-phase mixture density, void fraction, superficial liquid and gas velocities, liquid holdup, or visualization of the flow. These measurements are then analyzed for FIV prediction in terms of well-established dimensionless parameters and force correlations. Some of the important force correlations are discussed in Section 7. The prevalent measurement methods, principles and limitations for two-phase flow measurements are discussed in the following.

Density measurements: The simplest method to obtain the two-phase fluid mixture density is by means of weighing a section of the pipe or vessel, wherein the pipe section is mounted on load cells. Alternatively, the mixture may be extracted from a pipe section by using quick closing valves. The pipe deflection due to its own weight and the deflection with the conveying fluid are used to estimate the mixture density. These preliminary methods are uncomplicated but are limited to simple conditions. However, they have the advantage of not needing calibration.

Advanced densitometry techniques involve the use of pipe frequency measurements, ultrasonic waves, gamma rays, or X-rays. The vibrating tube technique has been applied recently for two-phase flow density measurements by Fu et al. (2020) and Dakkach et al. (2018). An external transverse excitation force is applied to the pipe conveying the two-phase fluid, and the frequency response is compared to the natural frequency of the empty pipe. The density of the mixture is then estimated. For a periodic excitation applied to the tube, the tube natural frequency $\omega_0$ and the frequency of the tube with fluid flow, $\omega$, can be used to estimate the mass of the fluid being conveyed as follows:

$$\frac{M_F + M_T}{M_T} = \left(\frac{\omega_0}{\omega}\right)^2$$

(1)

In the above equation, $M_T$ is the pipe/tube mass for the pipe section, and $M_F$ is the mass of the fluid mixture within the pipe. The above equation would be modified in the case of viscous damping (Retsina et al., 1987).
When ultrasonic waves traverse through a medium, they are attenuated, and the attenuation depends on the properties of the medium through which the waves are transmitted (Tan et al., 2021). This principle can be used for determination of interfacial area concentration, gas-bubble diameter, and void fraction, by applying two or three different acoustic frequencies to the pipe and analyzing the attenuation from the following equation.

\[
\frac{I}{I_0} = \left(\frac{A}{A_0}\right)^2 = \exp(-\alpha x)
\]  

(2)

In the above equation, \(I_0\) (or \(A_0\)) is the acoustic wave intensity (or amplitude) for the empty pipe, \(I\) (or \(A\)) is the acoustic wave intensity (or amplitude) through the pipe conveying two-phase fluid, \(x\) is the length over which the sound wave is attenuated, and \(\alpha\) is the attenuation coefficient (Bensler et al., 1987). However, this technique is primarily meant for bubbly two-phase flows and is unsuitable for other flow regimes. The schematic of the acoustic attenuation method is shown in Figure 3.

The electrical impedance method is used for measuring two-phase parameters such as void fraction, density, mixture velocity or mixture velocity. The method has been in use since the last four decades and there are ongoing advances on this method (Bertola, 2003; Ceccio & George, 1996; Dang, 2020; Dos Santos et al., 2018; Ghendour et al., 2021; Khambampati et al., 2015; Morse et al., 2021; Da Silva, 2008). The electrical impedance of two-phase flow depends on the phase composition of the mixture, the phase distribution, and the flow regime. The method is attractive due to its simplicity and quick response. Impedance methods are classified broadly as resistive/conductive and capacitive (capacitance) methods. The resistive/conductive method employs the variation of two-phase electrical resistance/conductance with the change in flow composition. The electrical impedance across an electrode pair becomes resistive for lower frequencies (10–100 kHz for tap water), whereas it becomes capacitive for frequencies of the order of 1 MHz. The electrodes are usually placed diametrically opposite in contact with the pipe external surface, or internally, in contact with the fluid. The capacitance method may be preferable since the change in mixture capacitance (or permittivity) is unaffected by external factors such as temperature; this is not the case with mixture resistance. However, sensitivity to the flow regime is a drawback of this technique. A relation between the void fraction (\(\epsilon\)), impedance (\(Z\)), and conductivity (or, dielectric...
constant, depending on whether the conductance or capacitance is employed for the measurement) may be derived. For the case of bubbly flow, the void fraction is given as

$$\varepsilon_g = \frac{A - Ac}{A + 2Ac} \left[ \frac{C_g + 2Cl}{C_g - Cl} \right]$$

(3)

The subscripts G and L indicate the gas phase and the liquid phase, respectively. A_c refers to the admittance in the case when the liquid phase alone is present. Each sensor is composed of a pair of electrodes, and a variable electric field is applied between the electrodes. The dielectric field, quantified by the dielectric permittivity, is induced within the two-phase medium due to the external electric field. Since the method delivers a quick response, it can also be used for mixture velocity determination with electrodes placed consecutively along the pipe length, in combination with the autocorrelation technique.

Gamma beam attenuation techniques make use of the property of gamma ray attenuation as they pass through a medium. The attenuation is dependent on the properties of the two-phase mixture constituents. These methods of measurement are classified as single beam, multiple beam, or broad beam types (Abbagoni et al., 2022; Baba et al., 2020; Salgado et al., 2020; Y. Zhao et al., 2016). A thin collimated gamma beam emitted from a radioactive source is transmitted through a pipe conveying a two-phase flow and is collected by a collimated detector (Figure 4). Attenuation of the beam may occur due to the Photoelectric Effect, Pair Production, or Compton Effect. The attenuation may also occur due to a combination of these effects. The gamma beam intensity at the detector is expressed as

$$I_d = I_0 \exp(-\mu_1 z_1) \exp(-\mu_2 z_2) \cdots \exp(-\mu_n z_n)$$

(4)

In the above equation, \(\mu_1\) refers to the linear absorption coefficient through the medium 1, and \(z_1\) refers to the length of the path traversed by the beam through medium 1. Subscriptions 1, 2 \(\cdots\) \(n\) refer to different media, which may be the pipe wall, or each distinct phase flowing within the pipe. The gamma ray device is calibrated by measuring the respective intensities for each phase separately flowing in the pipe. The void fraction for a gas-liquid flow can be easily derived starting from Equation (4) as

$$\varepsilon_g = \frac{\ln I - \ln I_L}{\ln I_G - \ln I_L}$$

(5)

The above equation is modified for hard radioactive sources (sources with low beam attenuation, e.g., Caesium-137) as

$$\varepsilon_g = \frac{I - I_L}{I_G - I_L}$$

(6)

The X-ray beam attenuation method is similar in principle to the gamma ray attenuation method. Recent applications of the X-ray beam attenuation method are given by Breitenmoser et al. (2021) and Rossi et al. (2018). The single gamma beam technique can only provide measurements along the beam path. This is unsuitable for area-averaged measurements across the pipe cross section. For this purpose, broad beam gamma ray techniques are in use (Hanus et al., 2018; Nazemi et al., 2016; Roshani et al., 2015, 2017). In the broad beam method, instead of a collimated beam, a diverging gamma beam covering the entire pipe diameter is used.
The multi-beam gamma technique is an extension of the single gamma beam technique. The method uses multiple gamma beams and has the advantage of providing instantaneous void fraction profiles and is used for unsteady tests in nuclear experiments and also in sub-sea and terrestrial oil-extraction industries. Multi-beam gamma ray method is non-invasive and can provide real-time, transient measurements. Due to the emergence of marginal oil-wells, slug formation has become a significant problem (Jacobsen, 2016) in the oil-extraction industry. As a result, real-time transient measurements are important for slug detection in sub-sea and terrestrial oil-extraction. A recent application of the multi-beam method in two-phase oil extraction/transport application is provided by Halstensen et al. (2014) and Hoffman and Hoffmann and Johnson (2011).

Gamma ray scattering and resultant attenuation occurs due to the Compton Effect. The principle has been used in gamma ray scattering method for void fraction measurements (El Abd, 2014). However, the method involves photon counting for up to one-hour duration in combination with high source strength beams. They are therefore limited to research applications alone.

Microwave attenuation involves microwaves in the electromagnetic spectrum. The method has potential for small-scale applications alone, such as oil-water sampling lines. Additionally, the presence of gas is likely to make the method unreliable. Recently, the microwave technique was used for two-phase flow measurements by Lin et al. (2020) and C. Zhao et al. (2019).

Neutron beam and neutron scattering techniques are, in principle, able to detect void fractions in two-phase flows. However, they have not been employed in practical studies so far.

### 2.2. Two-phase flow visualization techniques

Two-phase flow imaging is needed to visualize and understand the flow-regime. Tomography is a well-established method for flow visualization and involves imaging by sections through the use of penetrating waves that may be based on X-rays, nuclear, optical, ultrasonic, and microwave.

X-Ray visualization has been extensively used for imaging of two-phase flows. Aliseda and Heindel (2021) give an excellent review of the X-Ray imaging method for two-phase flows. In X-ray tomography, X-rays travel through a two-phase medium where they are attenuated. The beam attenuation is used to estimate the local density integral along the beam path. Various such beams are applied at different angles and the image is reconstructed so that an image of the density distribution of the phases is obtained.

The gamma-ray method is, in principle, similar to the X-ray imaging method with the difference that it makes use of a source of gamma rays from radioisotopes. Johansen (2015) and Bieberle et al. (2013) describe the principles and applications of radiation-based tomography. Yan et al. (2021) designed a fast Computed Tomography (CT) for two-phase flow using gamma rays and used Genetic Algorithms (GA) for quick image reconstruction. An industrial tomography application with the simultaneous use of two different radioisotopes was shown by De Mesquita et al. (2016). They demonstrated quicker signal processing, and higher temporal and spatial resolution with the technique. Due to the smaller detector size, and the lengthy process of obtaining photon counts, the gamma-ray imaging method is not used for transient flow studies.

X-ray tomography has a higher resolution compared to the gamma ray method, which employs a smaller detector. The former is also safer since the radioactivity of the radioisotopes cannot be controlled as in the case of X-rays (Taye et al., 1996).
| Pipe ID, Bend Radius ($R_b$) | Pipe orientation, Two-phase (air-water) | $j_g$ (Superficial Gas Velocity)/gas flow rate | $j_l$ (Superficial Liquid Velocity)/liquid flow rate | Pressure, Dynamic force measurement technique | Reference |
|-----------------------------|----------------------------------------|---------------------------------------------|------------------------------------------------|-----------------------------------------------|------------|
| 2.54 cm ID; 1/2 inch Diameter Orifice | Horizontal, Flow Restricting Orifice | 0.0069–1.7 m/s | 0.46–1.3 m/s | Capacitance Sensor, Laser Vibration Sensors | Bamidele et al. (2021) and Bamidele et al. (2019) |
| 52.5 mm | Horizontal | 0.1-4 m/s | 0.15–3 m/s | Accelerometer, Pressure Differential Pressure Transmitter | Carvalho et al. (2019) |
| D = 0.15 m; $R_b = 1.5$–$3.3$ D | Horizontal-Bend-Vertical | 0.9–40.6 m/s | 0.001–4.03 m/s | Force Ring, Strain Gauge, Piezo Strain Gauge | Belfroid et al. (2016, 2018) |
| 20.4 mm ID | Horizontal | 0.05–2.49 m/s | 0.26–6.3 m/s | Accelerometer | Ortiz-Vidal et al. (2014, 2017) |
| 50.8 mm ID, $R_o = 76.2$ mm | Vertical (Upward)-Horizontal | 0.1–18 m/s | 0.6–2.31 m/s | Pressure transducer, Triaxial force transducer, | Y. Liu et al. (2012) |
| 6 mm ID; 16.5 mm ID, $R_o = 25$ mm | Horizontal | (0.02–3.36) $\times 10^{-3}$ kg/s | (0.8–35) $\times 10^{-3}$ kg/s | Dynamic pressure transducer; Force sensor | Cargnelutti et al. (2009, 2010) |
| 25 mm ID | Horizontal | 0.1–70 m/s | 0.05–2 m/s | Dynamic pressure transducer; Force sensor | Belfroid et al. (2010) |
| 206 mm ID, 0.5 < $R/d$ < 6 | Vertical Riser | 0.1 to 10 m/s | 0.17–1.25 m/s | Piezoelectric | Riverin et al. (2006), Riverin and Pettigrew (2007) |
| 70 mm ID, Bend Radius ($R_b$) = 105 mm | Horizontal | 0.38–2.87 m/s | 0.2–0.7 m/s | Pressure transducers at bend inlet, exit, Quartz force sensor | Wang and Shoji (2002) |
Electrical Capacitance Tomography uses image reconstruction based on the dielectric properties of the flow phases (Fiderek et al., 2017; Yang et al., 2022). Sensors are mounted around the pipe circumference. Each sensor has a pair of electrodes that are placed on the pipe at diametrically opposite locations. The capacitances are measured after applying a time varying voltage to the sensors. From the capacitance measurements, an image of the permittivity distribution is reconstructed. The image resolution from ECT is low, but the images can be generated quite quickly, at 100 frames per second (Byars, 2001). ECT images are also less prone to statistical errors compared to the gamma-ray method. However, the gamma-ray and X-ray imaging methods provide a better image resolution compared to ECT in which the acquired data is subject to some ambiguity (Hu et al., 2005).

In addition to the above mentioned imaging methods for two-phase flows, less frequently used methods for two-phase flows are, as mentioned by Aliseda and Heindel (2021): “Microwave Computed Tomography (Mallach et al., 2017), Laser Induced Fluorescence (LIF; Farias et al., 2012; Voulgaropoulos et al., 2022, 2021), Positron Emission Tomography (Fishwick et al., 2005; Pore et al., 2015), Magnetic Resonance Imaging (Gladden & Sederman, 2013; Sederman, 2015), Electrical Impedance Tomography (Wang, 2015a, 2015b), and Ultrasound/acoustic CT (Rahiman et al., 2016; Watson, 2015)”.

2.3. Two-phase FIV: Literature overview
Two-phase flows are characterized by local fluctuations of pressure, momentum, density, void fraction, etc. (Akagawa, 1974; Ishii & Hibiki, 2011; Pettigrew & Knowles, 1997; Wallis, 1969; Yih & Griffith, 1968). Problems of wear, fatigue, and component failure or damage due to resonance can occur due to these fluctuating quantities, primarily due to void fraction (Bamidele et al., 2022, 2019; Hara, 1975; Ishii, 1977; Y. Liu et al., 2012; Miwa et al., 2014c). The literature on the internal flow is much smaller compared to external, two-phase, axial-flow and cross-flow.

For internal flows, elements such as elbows and Tees are known to be agents of FIV as they create changes in momentum, pressure, and separation of flow (Bamidele et al., 2019; Belfroid et al., 2010, 2016; Cargnelutti et al., 2009; Carvalho et al., 2019; Weaver et al., 2000). Vibrations arising from the flow are most prominent in the slug flow regime (Bamidele et al., 2019, 2022, 2021; Belfroid et al., 2016; Riverin & Pettigrew, 2007). There exist sudden, large changes in momentum and pressure in the flow due to slug movement. Slug regime is also encountered during transient startup and shut down, or at low load conditions for a system actually designed to be operational in the steady-state annular flow regime. Regimes other than slug are also known to cause FIV due to bubble-induced turbulence and local fluctuations in void-fraction and velocity.

Many experimental efforts have focused on the prediction of FIV from frequency domain analysis, and some selected literatures are given in Table 1. Relevant correlations for two-phase flow-related FIV are provided by some researchers (Cargnelutti et al., 2010; Riverin & Pettigrew, 2007; Tay & Thorpe, 2004). The earliest study of experimental two-phase FIV is by Yih and Griffith (1968). They recorded experiments for various flow regimes including slug, churn, and annular flow regimes over a wide range of conditions, with pipe diameters ranging from 0.64 m to 2.5 cm and triangular, annular and rectangular pipe cross-sections.

The power spectrum density (PSD) of momentum fluctuations indicates that for all the tested conditions, the majority of the fluctuation energy lies below 50 Hz. This fact was also corroborated by others (Y. Liu et al., 2012; Riverin et al., 2006) and is now widely utilized in structure design wherein the structural fundamental frequency is kept much higher than 50 Hz by employing additional support structures. In the annular flow and slug flow regimes, high amplitude FIVs due to momentum fluctuations are caused by surface waves in the former and alternating liquid slugs and Taylor-bubbles in the latter. These two regimes were found to be most susceptible to momentum fluctuations and the resulting FIV. Differences in pipe geometry resulted in differing behavior in the context
of FIV. Rectangular cross-section pipes are more prone to FIVs due to their lower fundamental frequencies, which are in the range of the momentum fluctuation frequencies. For annular pipes with spacers between the annulus, PSD is very broadly distributed without noticeable peaks. This leads to the conclusion that spacers are instrumental in breaking down the effect of fluctuations and in FIV suppression. The effect of bends on FIV was found to be insignificant by Riverin and Pettigrew (2007). However, momentum fluctuations were found to increase with a reduction in pipe diameter; this was attributed to insufficient mixing compared to larger pipes, resulting in larger fluctuations. Additionally, reduced damping resulting from the lower mass of smaller diameter pipes was instrumental in more pronounced FIV. A critical non-dimensional, hydraulic pipe diameter $D^*_{\text{hyd}}$ was defined by Schlegel et al. (2012) as an extension of the work of Kataoka and Ishii (1987). For diameters higher than $D^*_{\text{hyd}}$, the Taylor bubbles could not be sustained in the pipe due to the instability of large bubbles/slabs. Enhanced mixing was observed above the critical hydraulic diameter, with the flow becoming more of a homogeneous mixture. This resulted in a decrease in flow fluctuations. The critical, non-dimensional, hydraulic diameter, $D^*_{\text{hyd}}$ was defined as

$$D^*_{\text{hyd}} = \frac{D_{\text{hyd}}}{\sqrt{g \rho}} \geq 40$$  \hspace{1cm} (7)

In Equation (7), $\sigma$, $\rho$ and $D_{\text{hyd}}$ are surface tension, density and hydraulic diameter, respectively. The result could be useful in designing pipes and flow conditions to avoid the slug flow regime.

In the above sections, general literature relating to internal, two-phase FIV is presented. In the following sections, specific aspects and systems susceptible to two-phase FIV are discussed. The first part of the following section deals with FIV in long riser pipelines, commonly employed in subsea operations or in the petroleum extraction industry. The second part presents a specific type of internal flow, namely the slug flow regime, as it is known to be the “problem area” regarding FIV in internal, two-phase flows.

3. Two-phase internal flows

3.1. Flows in pipeline-riser systems

Risers carry vertically upward, two-phase flows, and systems involving risers are common in subsea operations. Risers pose a different set of challenges compared to the piping structures that may be encountered commonly in industrial systems. For example, subsea risers are usually much longer and more flexible compared to the rigid, clamped pipes in most terrestrial applications. Their investigation has become more complex due to their use in deep sea conditions. Therefore, most of the investigations for pipeline-riser systems involve simplified prototypes or are computational in nature (Wang et al., 2018a, 2018b, 2018c). Some of the works relating to pipeline riser systems, including those for subsea operations are discussed.

In subsea pipelines, two-phase FIV can be a major challenge. Various two-phase regimes occur in such pipelines, such as bubbly, churn, slug, and annular flow. However, the slug flow regime is known to cause large forces due to the coupling of the slug frequency and the natural frequency of the pipe/structure, or even due to the collision of slugs with connecting joints such as pipe bends and tees. Li et al. (2016) conducted an FSI simulation using the commercial software, ANSYS®, for two-phase flow in a 6 m long pipe with diameter 3.3 cm. Air flow rate to water flow rate ratios were varied from 3:7 to 7:3. The lowest frequency of the structural vibrations was found to be in the range of 4.6 Hz to 5.2 Hz. The slug flow regime FIV was found to be around 5 Hz. Their results show that the pipeline natural frequency should not lie in the FIV frequency range since the coupling of structural frequency with large amplitude slug regime frequency would cause
structural damage due to resonance. The computational results were in line with experimental results. However, no new insights were gained from the computational approach regarding two-phase flow dynamics, or evolution mechanism of FIV.

Numerical analysis of vibrations due to slug flow regime on a subsea riser made of steel was done by Cabrera-Miranda and Paik (2019). Using an Euler-Bernoulli type analysis, they estimated the fatigue limit and ultimate induced stress; however, no experimental comparisons were made by them.

Experimental analysis of the two-phase system was conducted with a prototype using an inclined pipe connected to a long vertical riser by Wang et al. (2018a, 2018b, 2018c). Various flow regimes were observed by visualization techniques. Low-frequency vibrations were observed for the regimes considered. The highest frequency (0.33 Hz) and amplitude of vibrations were noticed for the slug flow regime. They could also confirm the experimentally established fact that short section and firm support structures are helpful in eliminating low frequency structural vibrations by decoupling structural vibrations from FIV. Additionally, the slug flow regime and stratified flow regime were deemed to be critical causal agents that could cause system failure. The computational results, however, were able to confirm the available experimental results, but did not offer any new insight into FIV.

A large diameter (61 cm), 30 m long pipe-section belonging to a two-phase (natural-gas & oil) processing plant was analyzed for structural integrity concerns using a finite element methodology coupled to computational fluid dynamics (Ong et al., 2017). The authors suggested that providing additional support elements to the pipe would enhance the structural stability. The results confirm the fact of experiment that providing piping support structures for shorter pipe sections would limit the coupling of FIV to the structural response. However, the computational results could not be used for enhanced insight into the FIV process.

Belfroid et al. (2016) studied the two-phase flow in a small diameter (15 cm) pipe experimentally. They employed two setup variations. In the first, they employed a horizontal pipe connected to a vertical riser by means of an elbow. In the second, a U-bend was attached to the horizontal pipe section in order to study the effect of upstream changes in the flow. Sensors and accelerometers were used to measure force and vibrations, along with electrical resistance technique for measuring void-fraction. Resonance was avoided by increasing the natural frequency of the structure as done by Y. Liu et al. (2012). Flow regimes from stratified to annular flow were...
investigated. They developed and tested correlations for slug and non-slug flow regimes, which would be presented in later sections.

Abdulkadir et al. (2015) compared the CFD results with experiments for slug flow in a vertical riser pipeline of 67 mm diameter. The results could characterize the slug flow regime reasonably well. However, predicting the film thickness from CFD was inaccurate. They suggested better computational approaches, including refining the computational grid, for predictions to match with the experimental results.

It is observed that subsea systems or practical industrial-scale systems are not amenable to experiments unless prototypes and simplified geometries are used. Therefore, due to the lack of experimental resources, these systems have been studied by some authors by simplified prototypes or computational methods. An experimental result that is endorsed by computational techniques is that short pipe sections due to close clamped supports result in higher structural vibrational frequencies. Therefore, structural vibration due to short clamped sections does not couple with the two-phase FIV. However, the computational results mostly support the experimental facts but have not provided new insights or flow features that may not have been predicted experimentally.

### 3.2. Slug flow regime related FIV

The slug flow regime has gained much attention in two-phase FIV studies because dominant, large amplitude FIVs are observed in this regime. Therefore, the slug flow regime is quite important for industrial FIV issues. The impact force due to slugs on elbow bends and the resulting effect on the structure was experimentally investigated by Y. Liu et al. (2012), and an Impact Force term was proposed. The Impact Force term was subsequently included in analytical models for FIV prediction (Miwa et al., 2016). The forces due to momentum and pressure fluctuations are the major force terms usually considered in slug flows. In addition to these, the effect of slug impact on elbow bends or the centrifugal force effect on radial bends was accounted for by the Impact Force term, which is primarily relevant for elbows and bends conveying slug flows. The time-varying impact force term to be incorporated in the force equation was shown to be

\[
F_{IF}(t) = \frac{1}{2} P_{2s}(t) A_{\text{eff}} \sqrt{\frac{2 P_0}{\rho_1(t)(1 - \alpha(t)) \rho_2(t) \rho_2(t)}} \sqrt{2 P_0 \frac{L_2}{L_f}}
\] (8)

The FFT of the force equation with the additional impact term could well predict the magnitude of the flow-induced force and its frequency for elbows and bends in all regimes ranging from bubbly flow to churning flow. The model with the included term was found to be suitable for both low relative velocity flows (homogeneous mixture model) and high relative velocity flows (slug, wavy and stratified flow), unlike other researchers (Belfroid et al., 2016) who had considered only the pressure and momentum contributions for the force model.

Schulkes (2011) void fraction correlation was used to fit the experimental data for slug flow by Belfroid et al. (2016). The non-dimensional, characteristic frequency of the flow also known as Strouhal number (Sr) was shown to be a product of three non-dimensional parameters, \( \Phi, \Psi \) and \( \Theta \). Sr could be expressed in terms of these three parameters, as shown in Figure 5. The frequency (f) in the calculation of Sr was obtained from the FFT of the liquid holdup measured upstream of the bend.
Additionally, with an increase in \( j_f \), the non-dimensional flow frequency (Strouhal Number) approached a constant value of 0.5 (Figure 5). The non-dimensional frequency was shown to be the highest for slug flow regime. The force fluctuations were found to be due to pressure and momentum fluctuations. The pressure fluctuation contribution to the vibration/force comes primarily from turbulence, and therefore the pressure fluctuation energy was found to be distributed over a wide range of frequencies.

The contribution of the pressure fluctuations to the force term is found to be predominant for churn flows, whereas for the slug flow regime, the momentum fluctuations contribute primarily to the force. Furthermore, the momentum fluctuations are attributed to the effect of density variations, which are reflected in terms of the measured liquid holdup variations. A relation between \( F_{RMS} \) and Weber number \( (We) \) was attained as: \( F_{RMS} = K(\rho_j j_f^2 A) We^{-0.4} \). A value of \( K \) equal to 25 was suggested for pipes with diameters greater than 6 inches, while \( K = 10 \) was suggested for smaller diameter pipes.

Similar to the above investigations, the work of Cargnelutti et al. (2009, 2010) supported the fact that maximum force fluctuation amplitudes are found for the slug flow regime. Recent investigations by Bamidele et al. (2022) have brought into focus the effect of bends on the flow pattern redistribution and the effect on FIV, particularly for the slug flow regime. Similar to the works of Belfroid et al. (2016), Y. Liu et al. (2012), and Miwa et al. (2014c), they found that bends that are placed upstream of the slug flow are the cause of excessive vibrations at downstream bend locations, due to the heightened momentum fluctuations of the slugs that have an impact on the bends, and also due to the effect of centrifugal forces that are present due to the bend radius. Besides the effect of bends on slug flow-related FIV, the investigation by Bamidele et al. (2019, 2021) revealed that the slug-flow regime was instrumental for higher amplitude and low-frequency vibrations that occurred downstream of a two-phase flow orifice. The flow downstream was modified due to the orifice, and for the slug flow case, the vibrations at the orifice were found to be close to the structural vibration frequency and also very close to slug-induced FIV. This suggests that flow restricting orifices should be carefully investigated in the slug-flow regime, just as in the cases of bends, T-joints, and similar connecting structures.

The above investigations reveal that the slug-flow regime contributes significantly more to the FIV when compared to other flow regimes. FIV is accentuated due to additional factors (or force terms) when bends or connecting structures are placed in the pipeline. This aspect is explained in the section on FIV Force correlations.

4. Parameters affecting FIV

4.1. Void fraction effect
Void fraction is an important parameter and its effect on two-phase FIV is studied by various researchers. A clear and distinct peak of force fluctuations in the frequency domain was observed for high void fraction (greater than 70%) from the experiments of Riverin et al. (2006), Riverin and Pettigrew (2007), and Yih and Griffith (1968). Also, momentum fluctuations of the flow were found to be highly correlated with the force fluctuations in the pipe. A distinct peak in the FFT of force fluctuations or critical frequency mentioned above was also noticed at the slug-annular transition by Y. Liu et al. (2012). A relationship was spotted between
the root mean square (RMS) of the force fluctuation signal and the superficial total flow velocity \( \beta \). It could be expressed as \( F_{\text{RMS}} = C f^p \). The maximum value of \( F_{\text{RMS}} \) was observed in the churn flow regime. Similar results indicating a linear increase in the amplitude of force fluctuations with increasing total superficial velocity and/or ratio of superficial gas to liquid velocity have been shown by other researchers as well (Bamidele et al., 2019, 2022; Carvalho et al., 2019; Y. Liu et al., 2012; Miwa et al., 2014a, 2014b, 2014c).

Similarly, void fraction fluctuations are usually the largest for slug/churn flows (Bamidele et al., 2019, 2022; Y. Liu et al., 2012). This confirms the fact that slug and churn flow are most susceptible to the generation of FIV in two-phase flow. An in-depth understanding and prediction of these flow regimes is therefore important for FIV prediction.

4.2. Pressure, surface tension and viscosity effects
The effect of internal pressure on FIV is curious and interesting. With an increase in pressure, the gas phase becomes denser. However, liquids do not exhibit compressibility even for very high pressures. Therefore, the gas bubbles would be smaller for higher system pressure, and their effect on the momentum and pressure fluctuations should be lowered. This hypothesis is endorsed by limited experiments. Yih and Griffith (1968) used two dimensionless terms to relate Froude number \( (Fr) \), Weber number \( (We) \), RMS of pressure, pipe diameter, peak characteristic flow frequency, and flow velocity and found agreement in their limited range of conditions.

FIV forces were found to be independent of surface tension and viscosity by Riverin and Pettigrew (2007). They evaluated the effect of surface tension and viscosity by using Weber number and Froude number, and the dimensionless groups proposed by Yih and Griffith (1968):

\[
W_{\infty}^{0.4} \frac{P_{\text{RMS}}}{P_{\text{ST}}} \times(\beta) \quad (10)
\]

\[
f_d \frac{D}{V} \sqrt{\frac{Fr}{We}} = Y(\beta) \quad (11)
\]

The above were incorporated into a unified expression in terms of void fraction \( (\alpha) \), as

\[
\frac{F_{\text{RMS}}}{P_{\text{ST}}} = B \left( \alpha, \frac{\rho_l}{\rho_g}, We, Re, Fr \right) \quad (12)
\]

However, they could not prove a definite relationship between force and viscosity/surface tension. Therefore, a simpler expression was proposed based on the modification of the above expressions, given as

\[
\frac{F_{\text{RMS}}}{P_{\text{ST}}} = B \frac{We^{-0.4}}{1 - \beta} = CW_{\text{e}^{-0.4}} \quad (13)
\]

The above equation was based on the assumption that surface tension and viscosity were of less importance (Tay & Thorpe, 2004). However, investigations of two-phase flows in 6-mm diameter bends (Cargnelutti et al., 2009, 2010) could not reveal a good correlation between force fluctuations and Weber number alone from the previous equation. Therefore, neglecting the surface tension, gravity and viscosity effects altogether would be erroneous for FIV calculations.
4.3. Two-phase flow-damping effect

Some flow characteristics/regimes could be effective in damping the flow momentum fluctuations. However, experiments studying the relation between surface tension and damping could not find consistent results over all conditions (Pettigrew & Knowles, 1997; Weaver et al., 2000). A peak in flow-regime related transition was observed for bubbly to slug flow transition regime (Beguin et al., 2009). It decreases with increasing void fraction, that is, for slug and churn flow regimes. This is supported by the fact that maximum momentum fluctuations are observed for slug and churn regimes, especially at the slug-churn transition. FFT and PSD analyses of the vibration (displacement) and force signals indicate that clear peaks in FIV frequencies occur for the slug and churn flow regimes. On the other hand, the energy distribution over the frequencies is broadly distributed and there is no clear peak, for two-phase regimes other than slug and churn. Therefore, for regimes other than slug and churn flow, it may be deduced that FIV may be more easily absorbed/damped since the energies are not concentrated at particular frequencies but are rather broadly distributed over a wide range of frequencies. These facts were supported by the investigations of Y. Liu et al. (2012). Additionally, Y. Liu et al. (2012) found that FIV damping was lower for smaller diameter pipes, attributed to the low inertia of the pipes. The damping was also seen to decrease with increase in the interfacial area between the liquid and gaseous phases as in the case for low velocity bubbly flows.

5. FIV spectral analysis

Following the investigation of Yih and Griffith (1968), various researchers have used spectral techniques for the FIV studies. In these studies, Fast Fourier Transform (FFT) technique and Power Spectrum Density (PSD) of the force signal are used.

The maximum PSD frequencies obtained from pressure signals at a T junction were analyzed for various gas-to-liquid flow rate ratios (M_R) in the churn flow regime (Wang & Shoji, 2002). The maximum frequency was close to 0.18 Hz for 0.2 < M_R < 0.3, whereas it was equal to 1.6 Hz for M_R > 0.3.

Critically important sections of a Japanese Nuclear Reactor were investigated by Nakamura et al. (2005) using a 1/3 scale prototype. Pressure fluctuations at the U-bend connection between the sections were recorded. The PSD of pressure indicated that a peak frequency was observed just downstream of the U-bend, where flow separation was observed. The frequency correlated with Strouhal number (Sr = fD/U) equal to 0.45. Due to the flow separation effect at the bend, the maximum flow-induced vibrations were seen to occur downstream of the pipe bend.
Riverin and Pettigrew (2007) used normalized force spectra and frequency plots to show that for a given void fraction, the plots coincide for different tube geometries (Figure 6(a)). The normalized PSD and non-dimensional frequency were written as

$$\text{PSD} = \frac{\text{PSD}}{(GD)^2}$$  \hspace{1cm} (14)

$$\bar{f} = \frac{fD}{j}$$ \hspace{1cm} (15)
In the above expression, the mass flux $\mathbf{G}$ is defined as
\[
\mathbf{G} = \left[ \alpha \rho_g + (1 - \alpha) \rho_l \right] \mathbf{j}
\]  

(16)

The correlation between the dimensionless terms is written as
\[
\frac{\text{PSD}(f)}{\text{PSD}(f_0)} \begin{cases} 
\frac{(f)}{(f_0)_{m_1}}^{m_1}; f \leq f_0, \\
\frac{(f)}{(f_0)_{m_2}}^{m_2}; f \geq f_0
\end{cases}
\]

(17)

In the above correlations, $f_0$, PSD($f_0$), $m_1$, and $m_2$ were found using least-squares curve fitting technique (Figure 6(b)). The above correlations would enable the prediction of excitation forces due to FIV, and the methods/results could be applied for force prediction in two-phase FIV investigations.

Prior to the work of Y. Liu et al. (2012), most investigations were not focused on separating the structural frequency from the FIV. These studies were focused on highlighting the effect of FIV on the structural response and were usually demonstrated in resonance or “close-to-resonance” operating conditions. This would have been desirable if FSI being investigated, but the focus was not on FSI. Moreover, in order to understand FSI, it is not necessary to operate close to resonance condition, which is detrimental to the structure. In order to gain a better understanding of two-phase flow dynamics, without the interference effect of the structure, Y. Liu et al. (2012) experimented with short-section clamped pipes so that the pipe-section natural frequency would be much higher than the FIV frequency. They were then able to analyze the vibration due to FIV without the interference of the structural response. They used PSD of the force fluctuations and void fraction and found that the peak frequency and force fluctuations reached their maximum values immediately after the superficial gas velocity ($\dot{u}_g$) increased from bubbly to slug flow, while keeping the superficial liquid velocities fixed. They also found from PSD analysis that bends could significantly damp FIVs, and also that the larger diameter bends provided more effective damping.

6. FIV and structural interaction
The interaction of FIV and structural vibration or FSI has not been sufficiently investigated experimentally. Paidoussis (1970) was a pioneer for analytical solution of dynamical effects on piping structures due to two-phase flows and structure interaction. Analytical solutions can provide a usable estimate of system stability for a given set of initial conditions. Wang et al. (2018b) carried out a dynamical analysis of a horizontal pipe carrying two-phase flow was carried out where the coupling analysis for fluid structure interaction between gas-liquid, slug flow and horizontal pipe structure was done by finite element analysis. Centrifugal, coriolis, flexural, structural damping, inertia and gravity terms were considered in the governing equations. Slug characteristics were seen to primarily influence coriolis and centrifugal force components. Higher slug transitional velocity was found to correlate with lower vibration amplitude, but the vibration response became intensified. The results are expected to be useful for pipe safety analysis and prediction.

Euler-Bernoulli beam theory along with homogeneous equilibrium model (Chu et al., 2011) model for multi-phase flow was used for a fluid structure interaction analysis (Xu et al., 2016). Vibration analysis was done for a tube clamped at two ends by coupling the dynamical equations for fluid and structure.
Non-linearity was accounted for by using a modified form of Lee and Chung (2002), along with the consideration of surge (Zhang & Huang, 2000). Differences in higher order predicted frequencies were observed even though the fundamental frequency was well predicted by the model for certain conditions. They concluded that the mathematical model has much scope for development; however, it is sufficiently close to predicting experimental vibration results for selected conditions.

An investigation focusing on damping, excitation mechanism, and hydrodynamic mass was carried out (Ortiz-Vidal & Rodriguez, 2011), where the vibration response of a horizontal pipe clamped at two ends was studied by analytical formulations and experimental measurements. The study constituted a wide range of two-phase flow regimes. A correlation was suggested between the shear velocity and the pipe's acceleration response; the shear velocity being the source of turbulence generated excitation mechanism affecting the pipe structure. The peak frequency of the structure was shown to be a function of the hydrodynamic mass, and in turn, the void fraction. It was shown that the total damping should include two-phase damping in addition to structural damping. The authors proposed further investigations by varying the pipe length and also pipe end conditions.

7. Force correlations for FIV
Many of the correlations from FIV investigations relate to the force prediction due to FIV. These correlations may be used for force prediction or as inputs to analytical or computational models. By means of the “Piston Flow Model” (PFM; Tay & Thorpe, 2004, 2014), a slug-flow induced force correlation was proposed for the case of horizontal pipe bends. The PFM is a one-dimensional model involving transient momentum equation, and it was shown that the model predicted experimental results fairly well, as compared to industrial, “thumb-rule” predictions. The effect of liquid and gas properties was incorporated in the model (Tay & Thorpe, 2004). It was observed that liquid holdup ($H_L$) dropped for higher surface tension fluids, and for higher flow rates. They included the effect of liquid holdup by using a normalized form of $F_{R,max}$ as $F_{R,max}/\rho_L H_L$. The latter agreed with experimental data to a closer degree (Figure 7).
In their work, $F_{R,max}$ was found from $F_{R}^2 = F_{r}^2 + F_{y}^2$, where

$$F_x = -\{ \rho A_j u_x + (P_{in} A - P_o A) \} + \{ \rho A_j \left[ \frac{\partial}{\partial l} \right] (\cos \theta) \} dl$$

$$F_y = -\{ \rho A_j u_y + (P_{in} A - P_o A) \} + \{ \rho A_j \left[ \frac{\partial}{\partial l} \right] (\sin \theta) \} dl$$

$$u_{slug} = 1.2(\bar{j}_f + \bar{j}_g) + (0.54 - 1.76Eo_0^{0.56})\left( \sqrt{gD} \right)$$

and,

$$Eo_d = \rho_l gD^{2/3}/\sigma$$

The PSD correlations for various flow regimes given by Riverin and Pettigrew (2007) are discussed in the section on spectral analysis. They also proposed a correlation for transverse vibration ($x$) prediction given as

$$\bar{x}^2 = \left[ \int_0^\infty \frac{1/k}{1 - (v/v_n)^2 - [2\zeta (v/v_n)]^2} PSD(v)/(GD)\right]^2 dv$$

In the above equation, $x$ is the mean square value of a response, $D$ is the pipe diameter, $v_n$ is the natural frequency, $G$ is two-phase mixture mass flux, $k$ is stiffness, and $\zeta$ is damping ratio.

They could predict the vibration response within 50% error, and as per the authors, given the uncertainty involved, the predictions were considered reasonable. A force correlation model covering broadly bubbly, slug, churn and annular regimes was developed (Y. Liu et al., 2012). The model required inputs of void fraction and pressure measurements at the elbow inlet and outlet. The force term was expressed as

$$F_{FS_x} \approx -A \int \frac{\partial}{\partial l} \left( \alpha_x p_j x \sin \theta \right) dl - A_j \left[ \alpha_x p_j \right]_{out} - P_{out} A + F_{IFx}$$

In the above, the last term is the “impact force” term that was caused by local vibrations at the elbow due to impact of slug on the elbow. A detailed derivation of the impact force term was done later (Miwa et al., 2014c). Recently, investigations were conducted by Bamidele et al. (2022) who used the FFT of void fraction at the bend and correlated it to two-phase flow parameters such as the superficial-phase velocities, slip ratio and the mass quality. Their force model included an “impact force term” similar to that of Miwa et al. (2014c) as mentioned above, by which they could predict the heightened vibrations due to the impact of slugs at the bends.

8. Conclusions

The review involves internal, two-phase flow-induced vibration (FIV). Relevant literature that has a unique contribution is presented. The problem areas pertaining to two-phase FIV systems such as these have been brought out. Future avenues of research for two-phase, internal FIV have been
identified. There is a need for enhanced computational methods for two-phase internal flows. Problem areas such as slug flow and annular flow regimes have been discussed. Specific sub-systems such as pipeline riser systems are discussed and the experimental lacunae in these are pointed out because of the difficulty of experimentation in harsh domains. There is a need to expand the experimental database for these flow regimes applied to practical, industrial scale multi-structural component flows.

FIV correlations, spectral analysis, analytical models, importance of slug flow regime, and effect of parameters, such as void fraction, pressure, and surface tension, are discussed. Some computational results are presented; however, there is no separate section as computational efforts are not developed to the stage where they could resolve industrial scale internal, two-phase flow-induced vibration problems. Furthermore, even though computational efforts are being employed for advanced prediction of FIV in advance, for avoidance of major or minor failures, they always need to be confirmed with experimental result database, which is still under development. For the CFD to be accurate there should be sufficient base or benchmarking solutions for two-phase, internal multi-structural flows; however, experiments for these are very few. Insufficient experimentation in this domain proves to be a bottleneck for computational techniques. Much work is available in the literature regarding external cross-flows and axial flows, but for internal two-phase flows, there is no comparative body of the literature. One reason for this could be the difficulty in obtaining non-intrusive and non-local or “area-averaged” measurements for internal two-phase flows accurately. Two-phase flow-related instrumentation techniques are therefore an important area of research and development and many needs to be done in the area. There is much scope for experiments concerning FIV and its sources, and how it links with the structure causing fluid structure interaction.

A significant amount of research concerning two-phase FIV in energy, power and process plants/systems is made available within the past two decades. However, much work needs to be done in various FIV-related areas. Some of the areas which would require attention for FIV problem resolution in the future are mentioned as follows: (a) benchmark experiments investigating FIV and FSI problems; (b) development of validated models for a wide range of FIV-FSI conditions; (c) advancement in computational power for the implementation of FIV problems at the industrial scale; (d) development of predictive methods for FIV and related structural response; (e) preventive methods for FIV such as active and passive flow controls; and (f) decoupling FIV (mass, momentum, turbulence, energy, vortex-induced, swirl-induced) with external excitations (structural, acoustic, mechanical, rotary equipment).

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**Nomenclature**

| Symbol | Description |
|--------|-------------|
| A      | Area        |
| D      | Pipe Diameter |
| G      | Two phase Mass Flux |
| L      | Length      |
| We     | Weber Number |
| Fr     | Froude Number |
| Re     | Reynold’s Number |
| Sr     | Strouhal Number |
| j      | Superficial Velocity |
| p      | pressure    |
| t      | time        |
| g      | acceleration due to gravity |
| x      | x-direction |

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References
Abbagari, B. M., Yeung, H., & Loo, L. (2022). Non-invasive measurement of oil-water two-phase flow in vertical pipe using ultrasonic Doppler sensor and gamma ray densitometer. Chemical Engineering Science, Part B, 248, 117218. https://doi.org/10.1016/j.ces.2021.117218
Abdulkadir, M., Hernandez-Perez, V., Lo, S., Lowndes, I. S., & Azzopardi, B. J. (2015). Comparison of experimental and Computational Fluid Dynamics (CFD) studies of slug flow in a vertical riser. Experimental Thermal and Fluid Science, 68, 468–483. https://doi.org/10.1016/j.expthermflusci.2015.06.004
Akagawa, K. (1974). Gas-liquid two-phase flow. Corona Press.
Al Asmi, K. R., & Seibi, A. C. (1998). Vibration induced fatigue failure of an impulse line. Engineering Failure Analysis, 4(2), 195–204. https://doi.org/10.1016/S1350-6307(98)00017-X
Allseda, A., & Heindel, T. J. (2021). X-ray flow visualization in multiphase flows. Annual Review of Fluid Mechanics, 53(1), 543–567. https://doi.org/10.1146/annurev-fluid-011916-060201
Anagnostopoulos, P. (2002). Flow-induced vibrations in engineering practice (1st ed.). WIT Press.
Azzopardi, B. (2006). Gas-liquid flows. Begell House.
Baba, Y. D., Ribeiro, J. X. F., Aliyu, A. M., Archibong-Eso, A., Abubakar, U. D., & Ehinmowo, A. B. (2020). Characteristics of horizontal gas-liquid two-phase flow measurement in a medium-sized pipe using gamma densitometry. Scientific African, 10, e00550. https://doi.org/10.1016/j.scifai.2020.e00550
Bamidele, O. E., Ahmed, W. H., & Hasson, M. (2019). Two-phase flow induced vibration of piping structure with flow restricting orifices. International Journal of Multiphase Flow, 113, 59–70. https://doi.org/10.1016/j.ijmultiphaseflow.2019.01.002
Bamidele, O. E., Hasson, M., & Ahmed, W. H. (2021). Flow induced vibration of two-phase flow passing through orifices under slug flow conditions. Journal of Fluids and Structures, 101, 103209. https://doi.org/10.1016/j.jfluidstructs.2020
Bamidele, O. E., Ahmed, W. H., & Hasson, M. (2022). Characterizing two-phase flow-induced vibration in piping structures with U-bends. International Journal of Multiphase Flow 151 1 100402 0310–9322. https://doi.org/10.1016/j.ijmultiphaseflow.2022.100402
Beguin, C., Ansclutter, F., Ross, A., Pettigrew, M. J., & Mureithi, N. W. (2009). Two-phase damping and interface surface area in tubes with vertical internal flow. Journal of Fluids and Structures, 25, 178–204. https://doi.org/10.1016/j.jfluidstructs.2008.03.011
Belfroid, S. P. C., Cargnelutti, M. F., Schiferli, W., van Osch M. (2010, August 1–5). Forces on bends and T-joints due to multiphase flow. In Proceedings of the ASME 2010 3rd joint US-european fluids engineering Summer meeting Montreal, Canada. August, 1-5, 2010 (USA: American Society of Mechanical Engineers). 613–619. https://asmedigitalcollection.asme.org/FEDSM/proceedings-abstract/FEDSM2010/54518/613/338755
Belfroid, S. P. C., Nennie, E., & Lewis, M. (2016). Multiphase forces on bends—Large scale 6-inch experiments. In Proceedings of the SPE annual technical conference and exhibition, SPE-181604-MS, Dubai, UAE. 26-28 September (Society of Petroleum Engineers)SPE-181604-MShttps://onepetroleum.org/SPEATCE/proceedings-abstract/16ATCE2-16ATCE/D021S028R001/185057
Belfroid, S. P. C., Nennie, E., & Lewis, M. (2018). Influence bend radius on multiphase flow induced forces on a bend structure. In Proceedings of the 9th International Symposium on Fluid-Structure Interactions, Flow-Sound Interactions, Flow-Induced Vibration & Noise, July 8-11, 2018, Toronto, Ontario, Canada.
Bensler, H. P., Delhaye, J. M., & Fouveau, C. (1987, August). Measurement of interfacial area in bubbly flows by means of an ultrasonic technique. In ANS proceedings - 1987 national heat transfer conference, 24th national heat transfer conference and exhibition Pittsburgh, USA. 9–12 August, 1987 19 (USA: American Nuclear Society)240–246 https://inis.iaea.org/search/search.aspx?orig_q=RN:19078364
Bertola, V. (2003). Two-phase flow measurement techniques. In V. Bertola (Ed.), Modelling and experimentation in two-phase flow. CISM courses and lectures no. 450. Springer 324.
Bieberle, A., Hörting, H.-U., Robha, S., Schubert, M., & Hampel, U. (2013). Gamma-ray computed tomography for imaging of multiphase flows. Chemie Ingenieur Technik, 85(7), 1002–1011. https://doi.org/10.1002/cite.201200250
Blevins, R. D. (1979). Flow-induced vibration in nuclear reactors: A review. Progress in Nuclear Energy, 4(1), 25–49. https://doi.org/10.1016/0149-1970(79)90008-8

Blevins, R. D. (1990). Flow-induced vibration (2nd ed.). USA Van Nostrand Reinhold.

Breitenmoser, D., Manera, A., Prasser, H.-M., Adams, R., & Petrov, V. (2021). High-resolution high-speed void fraction measurements in helically coiled tubes using X-ray radiography. Nuclear Engineering and Design, 373, 110888. https://doi.org/10.1016/j.nucengdes.2020.110888

Brennen, C. E. (2005). Fundamentals of multiphase flow. Cambridge University Press.

Byars, M. (2001). Developments in electrical capacitance tomography [Paper Presentation]. In Keynote Review of the Second World Congress on Industrial Process Tomography Tomography, Hannover, Germany

Cabrera-Miranda, J. M., & Paik, J. K. (2019). Two-phase flow induced vibrations in a marine riser conveying a fluid with rectangular pulse train mass. Ocean Engineering, 174, 71–83. https://doi.org/10.1016/j.oceaneng.2019.01.044

Cargnelutti, M. F., Belfroid, S. P. C., & Schiferli, W. (2009, July 26–30). Two-phase flow-induced forces on bends in small scale tubes. In Proceedings of the ASME 2009 pressure vessels and piping division conference, PVP 2009, 26–30 July, 2009 (Prague, Czech Republic, USA: American Society of Mechanical Engineers).

Cargnelutti, M. F., Belfroid, S. P. C., & Schiferli, W. (2010). Two-phase flow-induced forces on bends in small scale tubes. ASME Journal of Pressure Vessel Technology, 132(4), 1–7. https://doi.org/10.1115/1.4001523

Carvalho, F. D. C. T., Figueiredo, M. D. M. F., & Serpa, A. L. (2019). Flow pattern classification in liquid-gas flows using flow-induced vibration. Experimental Thermal and Fluid Science, 112, 0894–1077. https://doi.org/10.1016/j.expthermflusci.2019.109950

Ceccon, S. L., & George, D. L. (1996). A review of electrical impedance techniques for the measurement of multiphase flows. ASME Journal of Fluids Engineering, 118(2), 391-399. https://doi.org/10.1115/1.2817391

Chu, I. C., Chung, H. J., & Lee, S. I. (2011). Flow-induced vibration of nuclear steam generator U-tubes in two-phase flow. Nuclear Engineering and Design, 241(5), 1508–1515. https://doi.org/10.1016/j.nucengdes.2011.01.034

Cong, T., Tian, W., Su, G., Qiu, S., Xie, Y., & Yao, Y. (2014). Three-dimensional study on steady thermohydraulics characteristics in secondary side of steam generator. Progress in Nuclear Energy, 70, 188–198. https://doi.org/10.1016/j.pnucene.2013.08.011

Crowe, C. T. (Ed.). (2006). Multiphase flow handbook. Taylor & Francis.

da Silva, M. J. (2008). Impedance sensors for fast multiphase flow measurement and imaging [Doctoral dissertation]. Technische Universität Dresden.

Daskach, M., Muñoz-Rujas, N., Aguilar, F., Aloasi, F. E. M., & Montero, E. A. (2018). High pressure and high temperature volumetric properties of (2-propanol + di-isopropl ether) system. Fluid Phase Equilibria, 469, 33–39. https://doi.org/10.1016/j.fluid.2018.04.012

Dang, C. (2020). Imaging and fast features extraction of two-phase flows using electrical impedance tomography [Doctoral dissertation, École Centrale Marseille]. Physics [physics]. École Centrale Marseille, English. NNT: 2020ECDM0060f. https://tel.archives-ouvertes.fr/tel-03168817

de Mesquita, C. H., Velo, A. F., Carvalho, D. V. S., Martins, J. F. T., & Homada, M. M. (2016). Industrial tomography using three different gamma ray. Flow Measurement and Instrumentation, 47, 1–9. http://doi.org/10.1016/j.flowmeasinst.2015.10.001

Dos Santos, E. N., Wrasse, A. N., Vendruscolo, T. P., Reginaldo, N. S., Torelli, G., Alves, R. F., Naidek, B. P., Morales, R. E. M., & da Silva, M. J. (2018). Sensing platform for two-phase flow studies. IEEE Access, 7, 1–9. https://doi.org/10.1109/ACCESS.2018.2887309

El Abd, A. (2014). Intercomparison of gamma ray scattering and transmission techniques for gas volume fraction measurements in two phase pipe flow. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 735, 260–266. https://doi.org/10.1016/j.nima.2013.09.047

Falcone, G. (2009). Chapter 3 multiphase flow metering principles. G. F. G. Gioia Falcone & C. Alimonti (Eds.), Developments in petroleum science. (Vol. 54, pp. 33–45). Elsevier. https://doi.org/10.1016/S0037-7667(09)05403-X

Farias, P. S. C., Martins, F. J. W. A., Sampaio, L. E. B., Serfaty, R., & Azevedo, L. F. A. (2012). Liquid film characterization in horizontal, annular, two-phase, gas-liquid flow using time-resolved laser-induced fluorescence. Experiments in Fluids, 52(3), 633–645. https://doi.org/10.1007/s00348-011-1084-4

Fiderek, P., Kucharski, J., & Wujman, R. (2017). Fuzzy inference for two-phase gas-liquid flow type evaluation based on raw 3D ECT measurement data. Flow Measurement and Instrumentation, 54, 88–96. https://doi.org/10.1016/j.flowmeasinst.2016.12.010

Fishwick, R. P., Winterbottom, J. M., Parker, D. J., Fan, X., & Stitt, E. H. (2009). The use of positron emission particle tracking in the study of multiphase stirred tank reactor hydrodynamics. Canadian Journal of Chemical Engineering, 87(1), 97–103. http://dx.doi.org/10.1002/cjce.5450830117

Fu, Y., Voltz, A., Ahamada, S., Hu, H., & Coquelet, C. (2020). Density data for carbon dioxide (CO2) + trans,3,3,3-tetrafluoroprop-1-ene (R-1243ze(E)) mixture at temperatures from 283.32 to 353.02K and pressures up to 100MPa. International Journal of Refrigeration, 120, 430–444. https://doi.org/10.1016/j.ijrefrig.2020.06.006

Ghajar, A. J. (2003). Non-boiling heat transfer in gas-liquid flow in pipes: A tutorial. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 27(1), 66–73. https://doi.org/10.1590/S1516-54782005000100004

Ghendour, N., Aziz, A., Meribout, M., & Zeghloul, A. (2021). Modeling and design of a new conductance probe for gas void fraction measurement of two-phase flow through annulus. Flow Measurement and Instrumentation, 82, 102078. https://doi.org/10.1016/j.flowmeasinst.2021.102078

Gladden, L. F., & Sederman, A. J. (2013). Recent advances in flow MRI. Journal of Magnetic Resonance, 229, 1–11. https://doi.org/10.1016/j.jmr.2012.11.022

Halstensen, M., Amundsen, L., & Arvoh, B. K. (2014). Three-way PLS regression and dual energy gamma densitometry for prediction of total volume fractions and enhanced flow regime identification in
multiphase flow. Flow Measurement and Instrumentation, 40, 133–141. https://doi.org/10.1016/j.flowmeasinst.2014.09.006
Hanus, R., Zych, M., Kusy, M., Jaszczur, M., & Petryka, L. (2010). Identification of liquid-gas flow regime in a pipeline using gamma-ray absorption technique and computational intelligence methods. Flow Measurement and Instrumentation, 60, 17–23. https://doi.org/10.1016/j.flowmeasinst.2018.02.008
Hara, F. (1975). A theory on the two-phase flow induced vibrations in piping systems. In Transactions of the 3rd international conference on structural mechanics in reactor technology, paper no. D2/4.
Hoffmann, R., & Johnson, G. W. (2011). Measuring phase distribution in high pressure three-phase flow using gamma densitometry. Flow Measurement and Instrumentation, 22(5), 351–359. https://doi.org/10.1016/j.flowmeasinst.2011.02.005
Hu, B., Stewart, C., Hale, C. P., Lawrence, C. J., Hall, A. R. W., Zwiens, H., & Hewitt, G. F. (2005). Development of an X-ray computed tomography (CT) system with sparse sources: Application to three-phase pipe flow visualization. Experiments in Fluids, 39(4), 667–679. http://dx.doi.org/10.1007/s00061-003-480-5
Ishii, M. (1977). One-dimensional drift-flux model and constitutive equations for relative motion between phases in various two-phase flow regimes (Technical Report, ANL-77-47). Argonne National Laboratory. https://doi.org/10.2172/6871478
Ishii, M., & Hibiki, T. (2011). Thermo-fluid dynamics of two-phase flow. Springer.
Jacobsen, D. S. (2016). Study of slug flow in undulated horizontal wells [Master’s thesis]. University of Stavanger. https://uis.brage.unit.no/uis-xmlui/handle/11250/2409054
Johansen, G. A. (2015). Chapter 7 - Gamma-ray tomography. In M. Wang (Ed.), Woodhead Publishing series in electronic and optical materials, industrial tomography (pp. 197–222). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-118-4.00007-1
Kandasamy, R., Cui, F., Townsend, N., Foo, C. C., Guo, J., Shenoi, A., & Xiong, Y. (2016). A review of vibration control methods for marine offshore structures. Ocean Engineering, 127, 279–297. https://doi.org/10.1016/j.oceaneng.2016.10.001
Kataoka, I., & Ishii, M. (1987). Drift-flux model for large diameter pipe and new correlation for pool void fraction. International Journal of Heat and Mass Transfer, 30(9), 1927–1939. https://doi.org/10.1016/0017-9310(87)90251-1
Khambampati, A. K., Lee, Y.-G., Kim, K. Y., Jerger, D. W., & Kim, S. (2015). A meshless improved boundary distributed source method for two-phase flow monitoring using electrical resistance tomography. Engineering Analysis with Boundary Elements, 52, 1–15. https://doi.org/10.1016/j.enganabound.2014.11.008
Lee, S. I., & Chung, J. (2002). New non-linear modelling for vibration analysis of a straight pipe conveying fluid. Journal of Sound and Vibration, 254(2), 313–325. https://doi.org/10.1006/jsvi.2001.4097
Li, F., Cao, J., Duan, M., An, C, & Su, J. (2016). Two-phase flow induced vibration of subsea span pipeline. In Proceedings of the 26th international ocean and polar engineering conference, ISOPE-1:1-333.
Lin, X., Wang, H., Chen, Z., Zhang, H., & Li, Y. (2020). Measurement of the flow rate of oil and water using microwave and venturi sensors with end-to-end dual convolutional neural network. Measurement: Sensors, 10–12, 100018. https://doi.org/10.1016/j.measurement.2020.100018
Liu, Y., Miwa, S., Hibiki, T., Ishii, M., Kondo, Y., Morita, H., & Tanimoto, K. (2012). Experimental study of internal two-phase flow induced fluctuating force on a 90 degree elbow. Chemical Engineering Science, 76, 173–187. https://doi.org/10.1016/j.ces.2012.04.021
Liu, L., Shi, K., Fan, X., Tan, W., & Wang, Y. (2021). Risk and characteristics analysis of the flow-induced vibration of the dip tube in opposed multi-burner gasifier. Journal of Loss Prevention in the Process Industries, 71, 104508. https://doi.org/10.1016/j.jlp.2021.104508
Mallach, M., Gebhardt, P., & Musch, T. (2017). 2D microwave tomography system for imaging of multiphase flows in metal pipes. Flow Measurement and Instrumentation, Part A, 53, 80–88. https://doi.org/10.1016/j.flowmeasinst.2016.04.002
Miwa, S., Liu, Y., Hibiki, T., Ishii, M., Kondo, Y., Morita, H., & Tanimoto, K. (2014a). Study of unsteady gas-liquid two-phase flow induced force fluctuation (Part 1: Evaluation and modeling of two-phase flow induced force fluctuation). Transactions of Japanese Society of Mechanical Engineers, 80(809), 1–11.
Miwa, S., Liu, Y., Hibiki, T., Ishii, M., Kondo, Y., Morita, H., & Tanimoto, K. (2014b). Study of unsteady gas-liquid two-phase flow induced force fluctuation (Part 2: Horizontal-downward two-phase flow). Transactions of Japanese Society of Mechanical Engineers, 80(811), 1–11. https://doi.org/10.1299/transme.2014tep0046
Miwa, S., Liu, Y., Hibiki, T., Ishii, M., Kondo, Y., Morita, H., & Tanimoto, K. (2014c). Two phase flow induced vibration. In Proceedings of 22nd International Conference on Nuclear Engineering (ICONE22) (ASME) (pp. 7–11).
Miwa, S., Hibiki, T., & Mori, M. (2016). Analysis of flow-induced vibration due to stratified wavy two-phase flow. ASME Journal of Fluids Engineering, 138(9), 091302. https://doi.org/10.1115/1.4033371
Morse, R. W., Moreira, T. A., Chan, J., Dressler, K. M., Ribatski, G., Hurlburt, E. T., McCorrall, L. L., Nellis, G. F., & Berson, A. (2021). Critical heat flux and the dryout of liquid film in vertical two-phase annular flow. International Journal of Heat and Mass Transfer, 177, 121487. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121487
Nakamura, T., Shiraishi, T., Ishitani, Y., Watakabe, H., Sago, H., Fujii, T., Yamaguchi, A., & Konomura, M. (2005). July 17–21. Flow induced vibration of a large-diameter elbow piping based on random force measurement caused by conveying fluid (Visualization test results). In Proceedings of PVP2005, ASME pressure vessels and piping division conference (ASME).
Nazeri, E., Roshani, G. H., Feghi, S. A. H., Setayeshi, S., Zadeh, E. E., & Fatehi, A. (2016). Optimization of a method for identifying the flow regime and measuring void fraction in a broad beam gamma-ray attenuation technique. International Journal of Hydrogen Energy, 41(18), 7438–7444. https://doi.org/10.1016/j.ijhydene.2015.12.098
Ong, Z. C., Eng, H. C., & Noroozi, S. (2017). Non-destructive testing and assessment of a piping system with excessive vibration and recurrence crack issue: An industrial case study. Engineering Failure Analysis, 82,
Wang, S., & Shoji, M. (2002). Fluctuation characteristics of two-phase flow splitting at a vertical impacting T-junction. *International Journal of Multiphase Flows*, 28(12), 2007–2016. https://doi.org/10.1016/S0301-9322(02)00106-0

Wang, M. (2015a). Chapter 2 - Electrical impedance tomography. In M. Wang (Ed.), *Woodhead Publishing series in electronic and optical materials, number 71, industrial tomography. Systems and applications* (pp. 23–59). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-118-4.00002-2

Wang, M. (Ed.). (2015b). *Industrial tomography: Systems and applications* (Woodhead Publishing series in electronic and optical materials, number 71).

Wang, L., Yang, Y. R., Li, Y. X., & Wang, Y. T. (2018a). Resonance analyses of a pipeline-riser system conveying gas-liquid two-phase flow with flow-pattern evolution. *International Journal of Pressure Vessels and Piping*, 161, 15–27. https://doi.org/10.1016/j.ijpvp.2018.02.005

Wang, L., Yang, Y. R., Li, Y. X., & Wang, Y. T. (2018b). Dynamic behaviours of horizontal gas-liquid pipes subjected to hydrodynamic slug flow: Modelling and experiments. *International Journal of Pressure Vessels and Piping*, 161, 50–57. https://doi.org/10.1016/j.ijpvp.2018.02.005

Wang, L., Yang, Y. R., Liu, C., Li, Y., & Hu, Q. (2018c). Numerical investigation of dynamic response of a pipeline-riser system caused by severe slugging flow. *International Journal of Pressure Vessels and Piping*, 159, 15–27. https://doi.org/10.1016/j.ijpvp.2017.11.002

Watson, N. J. (2015). Chapter 9 - Ultrasound tomography. In M. Wang (Ed.), *Woodhead Publishing series in electronic and optical materials, industrial tomography* (pp. 235–261). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-118-4.00009-5

Weaver, D. S., Ziada, S., Au-Yang, M. K., Chen, S. S., Paidoussis, M. P., & Pettigrew, M. J. (2000). Flow induced vibrations in power and process plant components: Progress and prospects. *Journal of Pressure Vessel Technology, 122*(3), 339–348. https://doi.org/10.1115/1.1556190

Wörner, M. (2003). A compact introduction to the numerical modeling of multiphase flows (Report Forschungszentrum Karlsruhe, FZKA 6532). http://bibliothek.fzk.de/zb/berichte/FZKA6532.pdf

Xu, X., Liu, M., Ma, Y., & An, M. (2016). Effects of fluidized solid particles on vibration behaviors of a graphite tube evaporator with an internal vapor-liquid flow. *Applied Thermal Engineering, 100*, 1229–1244. https://doi.org/10.1016/j.applthermaleng.2015.12.126

Yan, M., Ma, B., Tian, B., Hu, G., Wu, R., & Wang, S. (2021). Design, simulation and reconstruction for a fast speed two-phase flow CT with 241Am gamma ray sources. *Annals of Nuclear Energy, 151*, 107970. https://doi.org/10.1016/j.anucene.2020.107970

Yang, K., Zhang, X., Li, M., Xiao, Q., & Wang, H. (2022). Measurement of mixing time in a gas-liquid mixing system stirred by top-blown air using ECT and image analysis. *Flow Measurement and Instrumentation, 84*, 102143. https://doi.org/10.1016/j.flowmeasinst.2022.102143

Yih, T. S., & Griffith, P. (1968). Unsteady momentum fluxes in two-phase flow and the vibration of nuclear reactor components (MIT Report, No. DSR 70318-58).

Zhang, L. X., & Huang, W. H. (2000). Nonlinear dynamical modeling of fluid-structure interaction of fluid-conveying pipes. *Journal of Hydrodynamics, 15*(1), 116–128.

Zhao, Y., Bi, Q., Yuan, Y., & Lv, H. (2016). Void fraction measurement in steam–water two-phase flow using the gamma ray attenuation under high pressure and high temperature evaporating conditions. *Flow Measurement and Instrumentation, 49*, 18–30. https://doi.org/10.1016/j.flowmeasinst.2016.03.002

Zhao, C., Wu, G., Zhang, H., & Li, Y. (2019). Measurement of water-to-liquid ratio of oil-water-gas three-phase flow using microwave time series method. *Measurement, 140*, 511–517. https://doi.org/10.1016/j.measurement.2019.03.054
