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An experimental investigation on the two-phase intermittent flow coupling with structural vibration of horizontal pipes

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Abstract. *Two-phase flow is typically found in several industrial applications, such as in the production and transportation of oil and gas in the petrochemical industry, in the catalytic cracking and microreactors in the chemical industry, and in nuclear reactor cooling pumps. Measurement of two-phase flow features is usually necessary and has been done in several ways, including pressure probes, resistive sensors, gamma-ray, wire-mesh sensor and many others. However, these are either intrusive or invasive techniques, which might be of challenging application in industrial environments, or rely on a radioactive source. Vibration-based measurement of two-phase flow in pipes stands out as a non-invasive/non-intrusive approach and, consequently, multiphase-flow induced vibration in pipes has receiving increasing attention in recent years. In this work, the dynamic behaviour of a horizontal tube conveying a two-phase gas-liquid flow is characterised based on indirect approaches, focusing on intermittent patterns. The phenomenon of fluid-structure coupling is investigated using acceleration and pressure measurement. An approach based on the estimation of frequency response function of the pressure and vibration at the liquid piston and Taylor bubble is proposed. The estimated coherence function can used as quantitative measure of the coupling. It is shown that there is a great vibration amplification at the cut-on frequencies of circumferential wave modes in pipes due to the corresponding structural wave and pressure coupling. The experimental results pave the way for innovative vibration-based measurement approaches.*

Keywords: *Multiphase flow, flow induced vibration, pipe acoustics*

1. INTRODUCTION

Two-phase flow is present in several industrial applications including the production and transportation of oil and gas in the petrochemical industry (Terenzi *et al.*, 2019). One characteristic of two-phase flow is the various different geometrical and composition configurations between the fluid phases, namely flow patterns. The geometrical configuration depends on the fluids properties, such as density, viscosity, surface tension and on the flow conditions, such as the flow rates, pipe diameter and slope, and so on (Shoham, 2006; Ishii and Hibiki, 2011). The precise identification the flow pattern and its features is relevant for industrial purposes, for instance in flow assurance problems which are related to the occurrence of an specific flow pattern (Shippen and Bailey, 2012).

In pipes conveying gas-liquid flow, an intermittent flow can be modelled as unit cell varying from an elongated air bubble with a liquid film in segregated (stratified) flow pattern to a liquid slug with or without dispersed gas bubbles (Taitel and Barnea, 1990; Fabre and Liné, 1992; Netto *et al.*, 1999), both connected by a turbulent recirculating zone (Ishii and Hibiki, 2011). Although much research effort has been made in last decades, modelling gas-liquid flows still depends on several experimental data and closure laws (Wu *et al.*, 2017). Thus, measurement of two-phase flow features is usually necessary and has been done in several ways, including pressure probes (Vieira *et al.*, 2021), resistive sensors (Santos *et al.*, 2019), gamma-ray (LI *et al.*, 2007), wire-mesh sensor (Peña and Rodriguez, 2015) and many others. However, these are either intrusive or invasive techniques, which might be of challenging application in industrial environments, or rely on a radioactive source.

In this context, vibration-based measurement of two-phase flow in pipes has the potential for standing out as a non-invasive/non-intrusive approach and. Very few research has been done at the structural wave behaviour of higher frequency dynamics of pipes conveying two-phase flow (Matos *et al.*, 2022; de M.C. Matos *et al.*, 2022). Unlike the typical modal approach, wave-based dynamics relies on the local properties of the pipe, which is very appealing considering the varying operational condition at industrial applications.

There is an extensive literature about vibroacoustics and acoustics of single phase fluid filled pies. More recently, Kirby and Duan (2019) demonstrated the phenomenon of energy transfer between the fundamental fluid type mode and some structural wave modes. Remarkably, there is a gap in the literature about the vibroacoustics of pipes conveying two-phase flow. In this study, an experimental investigation on the two-phase fluid-structure coupling is proposed for horizontal pipes conveying intermittent flow. Focus is given at frequency bands around the cut-on frequencies of the circumferential wave modes of the pipe. The pipe excitation and response are investigated from pressure and acceleration measurements. It is shown that the the pipe vibration response is significantly amplified at the circumferential wave modes cut-on frequencies.

The paper is organised such that Section 2.briefly reviews some fundamentals of two-phase flow in horizontal pipes, with focus on the dispersed bubble in the liquid piston. Section 3.presents the experimental setup used in this work. Section 4.presents the experimental results and discussion and Section 5.presents the conclusion and summarises the findings in this paper.

2. INTERMITTENT FLOW

The intermittent flow pattern is problematic for practical operations due to changes of moment and pressure fluctuations causing the pipe resonant oscillations (Hara, 1977; Miwa *et al.*, 2015). Then, fluid flow in pipes is a typical Fluid Structure Interaction (FSI) phenomenon, in which the flow excites the pipe and consequently it is deformed, named one-way coupling. On other hand, the two-way coupling consider that excitation of the flow causes deformations in the walls pipe and it also excites the flow (Mohmmed *et al.*, 2020). Nevertheless, due to its complexity, few studies have investigated two-way coupling, so it is mostly assumed the one-way coupling to analyse the dynamic response analytically and computationally. Figure 1 presents the physical model for slug flow. It consists of alternating repetitive arrangements, called unit cells with length L_U along the pipe with a characteristic frequency. These cells are composed of liquid pistons aerated by small dispersed bubbles of length L_S followed by a Taylor bubble of length L_F. In addition, there is a turbulence zone behind the Taylor bubble passage with length L_M.

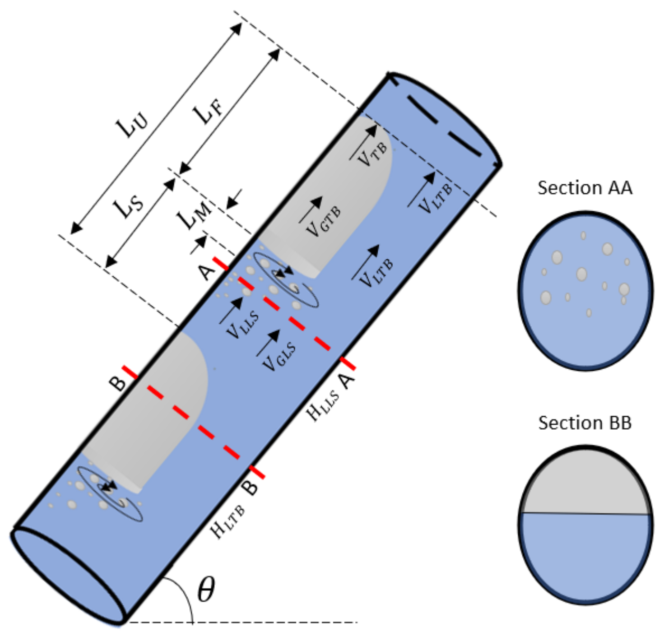

Figure 1: Slug flow geometric characteristics (adapted) (Shoham, 2006).

3. EXPERIMENTAL SETUP

The results presented in this work were obtained from tests carried out at the Experimental Laboratory of Petroleum - LabPetro - of the Center for Energy and Petroleum Studies - CEPETRO - at University of Campinas. A 20 meters long horizontal line of two-phase liquid-gas flow was developed, consisting of a 6-metres section of steel pipe with a 3" internal diameter and 4.5 mm of thickness. Tap water and compressed air were used as working fluids. The experimental bench had several sensors for synchronous measurement, from which a piezoelectric sensors 106B50 (model 2), an accelerometers model PCB 352C33 and one conductance-based void meter array with four sensors R_1, R_2, R_3, and R_4 Santos *et al.* (2019) are of interest for this work. The pressure sensor is setup at the bottom of the pipe while the accelerometer sensor is externally glued just above it, at the upper part of the pipe. The void fraction measurement is R_4 synchronised with the accelerometer, pressure sensor and the high-speed camera using the known distances in the bench and the velocity of the Taylor bubble, following the approach proposed by Vieira *et al.* (2023).

The acceleration and pressure time series were recorded at 25.6 kHz during 600 seconds using a National Instruments (NI) acquisition system. The void fraction measurements were performed at 400 Hz and up sampled to match the other measurements. Measurements were carried at flow conditions given by the liquid superficial velocities J_{sl}, gas superficial velocities J_{sg}, summarised in Table 1. It also shows average values for liquid piston length L_{slug}, Taylor bubble length L_{bubble}, frequency of passage of the unit cell, f_{slug} and its measured velocity V_{TB}, obtained from the void fraction measurements by applying the binarization approach proposed by Vieira *et al.* (2023).

Table 1: Experimental test matrix with liquid superficial velocities (J_{sl}), gas superficial velocities (J_{sg}), liquid piston length (L_{slug}), Taylor bubble length (L_{bubble}), and flow pattern, classified as Slug (SL).

Point	**J_{sl} [m/s]**	**J_{sg} [m/s]**	**J_m [m/s]**	L_{slug}**[m]**	L_{bubble} **[m]**	f_{slug} **[Hz]**	V_{TB} **[m/s]**	**Flow pattern**
13	1.354	1.402	2.756	1.065	2.313	0.890	3.05	SL

4. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, the experimental results are presented and discussed. The void fraction time samples are classified in Taylor bubble or liquid piston following the Otsu's method, which is a unsupervised and non-parametric approach Vieira *et al.* (2023) using R_4 conductance-based void fraction meter signal. The result is binarized time series, which is subsequently synchronised with acceleration and pressure sensors, based on the time delay estimated from a the Taylor bubble velocity, as shown in Figure 2. Thus, it is possible to determine the vibration and pressure instants which either the liquid slug or the Taylor bubble is at the sensor position.

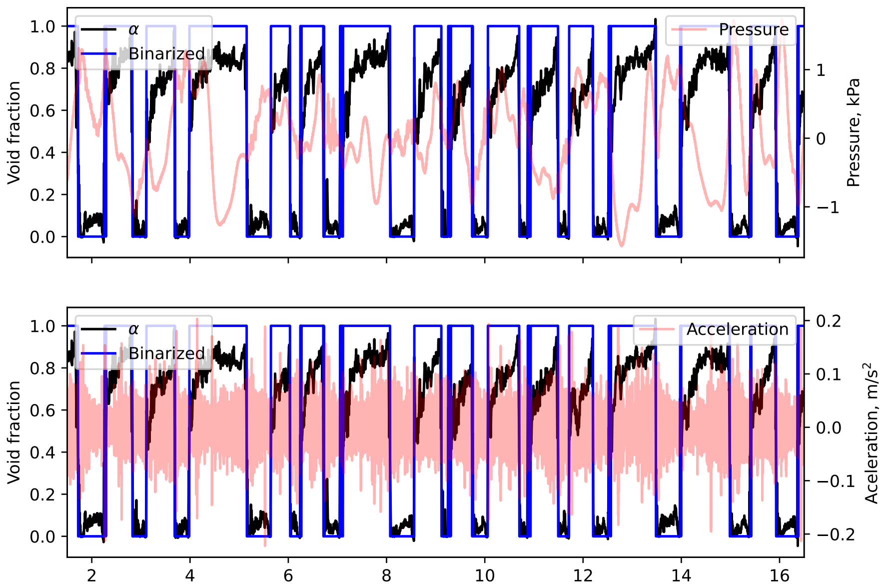

Figure 2: Measured pressure and acceleration signals along with the synchronised void fraction series and its corresponding binarized time series, in seconds.

The Taylor bubble velocity is be estimated based on time delay Δt_{TB} from measurements at two sensors at known distance d as

$$V_{TB} = \frac{d}{\Delta t_{TB}}. \tag{1}$$

Cross-correlation-based approaches can be used for estimating the time delay of the measured signals, defined as $R_{1,2}(\tau) = \mathbb{E}\left[\alpha_1(t)\alpha_2(t+\tau)\right]$, where τ is the time lag and $\alpha_1(t)$ and $\alpha_2(t)$ are the void fractions at each measurement position. This basic estimator can be greatly enhanced by generalised cross-correlation methods (GCC) Hassab and Boucher (1979). In this approach, a frequency domain pre-filtering is applied on the Cross-Power Spectral Density (CPSD), prior to the inverse Fourier transform, aiming at enhancing the signals with better signal-to-noise ratio (SNR) and to pre-whitening the signals are such that the peak of the cross-correlation is sharpened Gao *et al.* (2006). The generalised cross-correlation $R^g_{1,2}(\tau)$ in this case is given as

$$R^g_{1,2}(\tau) = \mathscr{F}^{-1}\left\{\Psi_g \omega S_{1,2}(\omega)\right\}, \tag{2}$$

where $\Psi_g(\omega)$ if the frequency weighing function.

Amongst the GCC methods, Vieira *et al.* (2023) showed that the smoothed coherence transform (SCOT) is very appealing for estimating the velocity of gas bubble because it combines a pre-withening, which removes the dispersive effects of travelling waves, with a weighting by the coherence function, which decreases the influence of frequency bands with low SNR. For the case of travelling bubbles, or mass waves, the wave dispersion is mostly due to changes on the format of the bubble along the pipe. The SCOT weighing is given by

$$\Psi_g(\omega) = \frac{\gamma_{1,2}(\omega)}{|S_{1,2}(\omega)|}, \tag{3}$$

where $\gamma_{1,2}(\omega)$ is the ordinary coherence function from the estimation of the CPSD Shin and Hammond (2008). The latter gives a frequency dependent measure of the linear relation between both sensors. It can be shown that $\gamma_{1,2}(\omega) = 1$ for linearly related signals and $\gamma_{1,2}(\omega) = 0$ for uncorrelated signals. Values in between indicate that the signals are only partially linearly related. Typically, this is due to noise contamination, the presence of extra sources affecting one of the sensors and/or non-linearities.

Figure 3 shows the Frequency Response Function (FRF) amplitude from the H_T estimator and the coherence function $\gamma(\omega)$ for the liquid piston (slug), the Taylor Bubble and the unit cell at the experimental points 13 and 17. Unlike the classical H_1 and H_2 estimators, the H_T assumes the same level of additive and uncorrelated measurement noise in both input and output Shin and Hammond (2008). The coherence function gives the level of linear relation between two signals and it is equal to unity for linearly related signals and zero for uncorrelated signals. The segment and average Welch's approach is used to estimate the auto and cross Power Spectral Density for the corresponding estimator. The segments are chosen from each flow structure in the slug unity cell, i.e., the liquid piston and the Taylor bubble, following the classification as presented in Figure 2. Consequently, the H_T estimator can be used for each flow structure, and also for each unit cell. Due to the stochastic nature of the slug flow, the averaging is computed by zero-padding each raw Power Spectral Density to the next power of the two of the largest cell in the measurement.

In the context of the H_T estimator, the coherence function can be smaller than one in case there is nonlinearities in the systems, measurement noise and more than one input for the same output. Assuming the pipe is operating in the linear regime, which is reasonable given the low pressure levels, and that the measurement noise is averaged out due to the significantly high number of segments in the 600 seconds of measurement, the values of the coherence function close to zero can be associated to more than one input to the acceleration response. This is expected due to the spatial coherence induced by Turbulent Boundary Layer (TBL) excitation Maxit *et al.* (2021).

It is interesting to note that the H_T estimate at the liquid piston yields close to zero coherence, while, it reaches values close to unity at the Taylor Bubble region, and at the full unit cell. This needs further investigation but it can be associate to pressure gradient along the pipe cross section. Remarkably, the coherence levels increase sharply at the cut-on frequencies and at a frequency band just below 1 kHz. Investigating the latter are outside the scope of this work. This highlights the localised nature of the coupling and the band limited characteristic of the two-way coupling between the pipe vibration and flow. From the modal point of view, the cut-on of a new structural wave mode substantially increases the modal density of the structure, as the added wave mode type can yield more vibration wave mode, thus increasing the vibration response in this frequency band. This fluid-structure coupling frequency can be approximately predicted from analytical expressions and can be used to further probe in the fluid flow in order to estimate two-phase flow patterns and its features.

5. CONCLUSIONS

In this work, an experimental investigation is carried out for the two-phase fluid-structure coupling for horizontal pipes conveying intermittent flow. The pipe excitation and response are investigated from pressure and acceleration

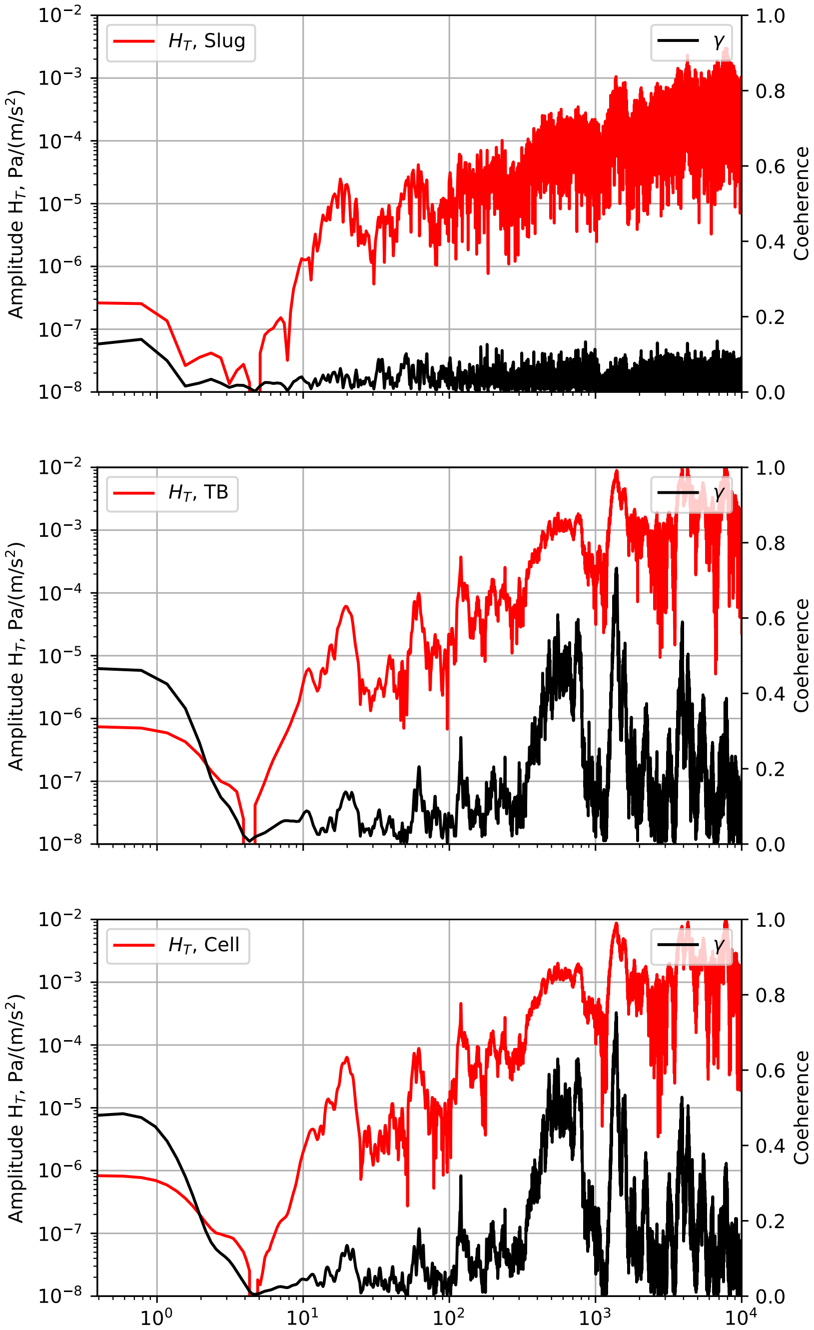

Figure 3: Amplitude of the estimated FRF and the coherence as a function of frequency in Hz at the liquid piston (Slug), Taylor bubble (TB) and the unit cell (Cell)

measurements. A classical Single Input/Single Output linear time invariant system identification approach is proposed to investigate the two-phase fluid/structure coupling at different frequency bands of the measurement. Results show that there is a localised coupling at a frequency band close to cut-on frequencies of structural wave modes, which are directly related to an increase on modal density of the pipe. Further work includes using these results to probe in the fluid flow in order to estimate two-phase flow patterns and its features from single point non-intrusive vibration measurements. The experimental results pave the way for innovative vibration-based measurement approaches.

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