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EXPERIMENTAL CHARACTERIZATION OF LINEAR INTERFACIAL WAVES IN HORIZONTAL STRATIFIED FLOW

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Abstract. *The evolution of interfacial waves on a stratified flow was investigated experimentally for air water flow in a horizontal pipe. Waves were introduced in the liquid level of stratified flow near the pipe entrance using an oscillating plate. Mean height of liquid layer and fluctuations superimposed to this mean level were captured using high speed cameras. Digital image processing techniques were used to detect instantaneous interfaces along the pipe. The driving signal of the oscillating plate was controlled by a D/A board that was synchronized with the acquisitions. This enabled to perform phase locked acquisitions and to use ensemble average procedures. Thereby, it was possible to measure the temporal and the spatial evolution of the disturbances introduced in the flow. In addition, phase locked measurements of the velocity field in the liquid layer were performed using standard planar PIV. The velocity fields were extracted at a fixed stream wise location, whereas the measurements of the liquid level were performed at several locations along the pipe. The assessment of the set-up was important for validation of the methodology proposed in this work since it aimed at providing results for further comparisons with theoretical models and numerical simulations. Results show that linear waves were observed for liquid level oscillations lower than about* 1.5% *of the pipe diameter. Eigenfunctions in the liquid layer related to interfacial modes were measured experimentally for the first time. For moderate holdup levels, the eigenfunctions clearly show that interfacial modes are decoupled from inner modes which are related to wall turbulence.*

Keywords: *Stratified two-phase flow, Instability, Gas-liquid, Kelvin-Helmholtz*

1. INTRODUCTION

The transport of gas and liquid simultaneously in horizontal pipelines is present in many engineering applications. During the last decades, an intense effort has been devoted to the study and modeling of the flow characteristics in order to increase safety and profit margins in pipeline operations, see Havre *et al.* (2000) for a review.

According to Kordyban and Ranov (1970), slug flow in horizontal pipes can be generated from stratified flow by hydrodynamic instabilities which promote growth of small perturbations present in the liquid interface. They have derived a criterion for transition based on inviscid linear stability analysis and discrepancies with experimental results of Wallis and Dodson (1973) were observed. Later, Lin and Hanratty (1986), Barnea and Taitel (1989), and Barnea and Taitel (1993) extended the linear stability analysis to include viscous effects, and derived a theoretical expression that showed reasonable agreement with reported low-pressure, small-scale data for low and medium gas flow rates. According to Bendiksen and Espedal (1992) and Kadri *et al.* (2009), for pipes with large diameters and high flow rates there is still a discrepancy between the experimental findings and the theoretical predictions.

Andreussi *et al.* (1985) showed that non-linear roll waves are possible solutions of the one-dimensional mass and momentum equations for gas and liquid. They suggested that the appearance of roll waves would be related to the slug initiation. Later Soleimani and Hanratty (2003) used viscous long wavelength theory to predict the initiation of roll-waves and consequently the slug onset. Many other subsequent works have been devoted to investigate and to model the slug initiation (Fan *et al.*, 1993; Ujang *et al.*, 2006; Valluri *et al.*, 2008; Ansari and Shokri, 2011). Although many aspects of the problem are included in the models, they are still not capable to accurately predict the slug onset for a wide range of pipe diameters and flow rates. Some authors, such as Bontozoglou (1991) claim that non-linear effects, which are not included in most models, can play a crucial role in the transition process. Recently, Sanchis *et al.* (2011) suggested that nonlinear wave interactions can induce a fast growth of fluctuations in the liquid level and initiate slugs.

A remarkable progress of numerical tools for simulation of two phase flows has been experienced in the last decades (Issa and Kempf, 2003). Some of these simulation tools are capable to predict terrain generated slugs, but they often fail in predicting the formation of hydrodynamic slugs. For instance, in Sanchis *et al.* (2011), it is mentioned that some commercial numerical simulation tools widely used in industry, such as OLGA®, are not capable to predict with reasonable

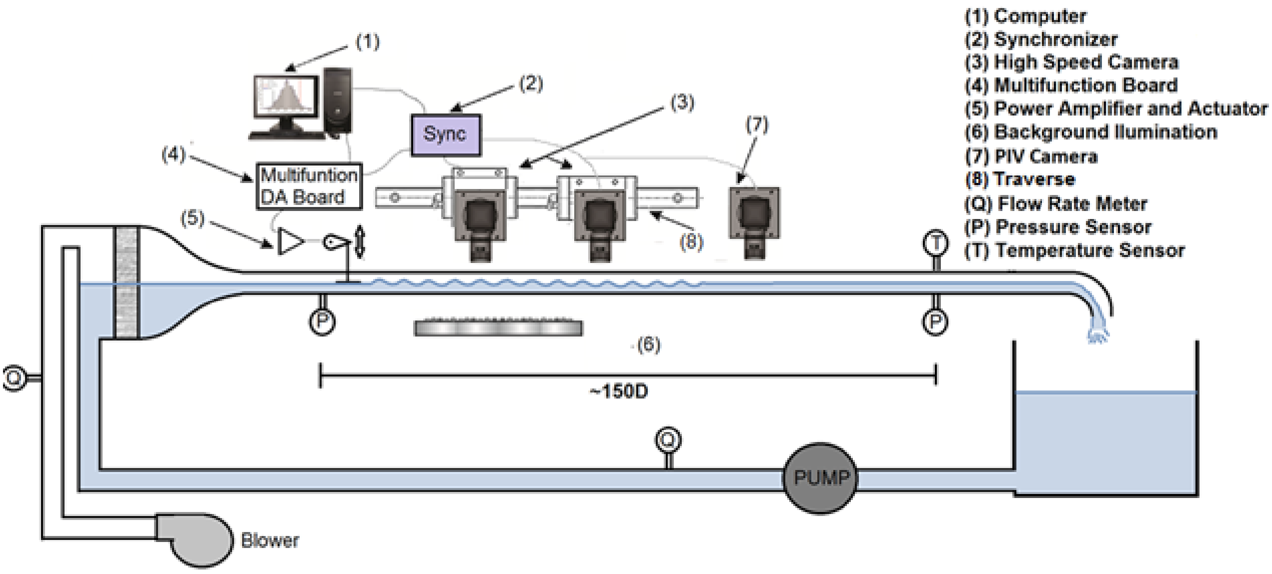


Figure 1: Schematic view of the experimental set-up used in this study.

accuracy the formation of hydrodynamic slugs.

Due to the complexity of the problem it is, indeed, very difficult to establish a unique model which can be used for a wide range of flow parameters. A common procedure used for validation of both theoretical and numerical models, is to correlate the predictions with the experimental data of slugs (see Sanchis *et al.* (2011) for a review). To this end, statistical data about the shedding frequency of slugs have been extensively used. For instance, the works Barnea and Taitel (1989), Barnea and Taitel (1993), Kadri *et al.* (2009) and Sanchis *et al.* (2011) did use such approach. Although, the slug statistics can be somehow influenced by the growth of disturbances that causes the slug initiation, it is not clear whether these disturbances are directly related to the shedding frequency. For a straightforward validation of models and simulations, it would be more convenient to have an experimental data base about the development of interfacial waves, since most of models are derived from modal stability analysis of well-defined base flows. However, the set-up required to introduce controlled disturbances with parameters similar to the most unstable eigenmodes, according to the stability analysis, is hard to implement and therefore it is not found in the literature.

The aim of the current work is to address this point by introducing controlled waves at the interface of the liquid in a stratified gas-liquid flow. The disturbances are introduced near the pipe entrance and their evolution is analyzed for different mixture Froude numbers

2. SET-UP

A schematic view of the test rig used in the experiment is presented in Figure 1. The pipe line was fabricated from Fluorinated Ethylene Propylene (FEP) with internal diameter (D) of 0.0508 m and length (L) of 8m, yielding 150-diameter-long tube. FEP material has nearly the same refractive index as water providing reduced light scattering and allowing the liquid film visualization at regions very close to the pipe wall (Hewitt *et al.*, 1990).

Air was supplied to the test section by a centrifugal compressor with velocities up to 40 m/s. Superficial liquid velocities up to 0.5 m/s are provided by a progressive cavity pump. Air and water flow rates were measured using calibrated turbines, CONTECH models SVTG G19 and SVTL L19, with experimental uncertainties estimated to be within 1% and 0.5%, respectively. Air and water were injected by special mixer that was designed using concepts usually employed in low turbulence water tunnel facilities (Wetzel and Arndt, 1994). The mixer was located at the inlet section of the tube. The flow conditioners are introduced downstream of the settling chamber in order to remove swirl and fluctuations of high amplitude. Further downstream a contraction with cubic shape, designed according to Wetzel and Arndt (1994), provides a smooth acceleration of both fluids toward the pipe inlet.

Controlled disturbances are generated at the liquid-gas interface near the pipe entrance using an oscillating plate. A multifunction D/A board NI AT-MIO-16X was used to control the movement of the oscillating plate. This setup is capable to generate arbitrary waveforms. A power amplifier with unity gain was used to drive the actuator, that consists of the head positioning system of a common hard disk drive.

Images of the liquid film were captured using two IDT Motion Pro X3 high frame rate cameras with 1.3MPixels. Approximately 20 pipe diameters from the wave generation source, the cameras were mounted orthogonally to a high

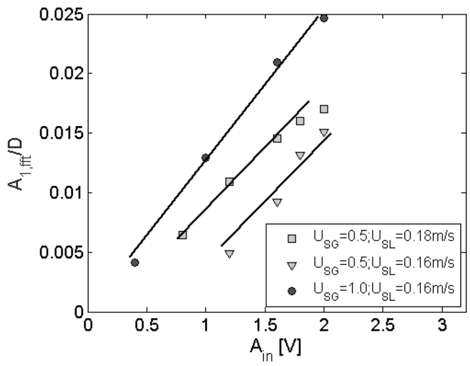


Figure 2: Variation of wave amplitude at the last measurement station according to the forcing amplitude.

power white LEDŠs light sheet panel, which provide with proper contrast background illumination for image acquisition. A synchronizer BNC 575 allowed the synchronization between the generation of disturbances and the image acquisition. An image processing algorithm was developed to automatically detect the position of the air-water interface in each image frame.

2.1 Analysis of velocity fields in the liquid layer

Velocity fields in the liquid layer were measured with a planar PIV set-up, which consisted of one TSI Powerplus 4MP camera with resolution 2048×2048 and a double-pulse Nd:YAG laser of 200mJ per laser pulse. Due to optical alignment the camera and the laser optics were placed at a fixed position. Thus, the velocity fields were obtained for a single streamwise location corresponding to 100D from the pipe inlet. Furthermore, the test section was equipped with a rectangular optical box filled with water, matching the refracting index of the FEP pipe, hence reducing distortion caused by the pipe wall. The water was seeded with spherical polyamide particles with $\bar{d} \sim 50\mu m$ and with nearly zero buoyancy.

Sets of 1000 image pairs were acquired. The interrogation process of the recorded PIV realizations was carried out with TSI's commercial software, Insight 4G, using 64×64 pixels interrogation windows with 50% overlap. Hence, the final sub-window size was 32×32 pixels, resulting in 63 displacement vectors in each spacial direction (x and y).

The acquisitions were synchronized with the disturbance source. Thereby, ensemble average techniques could be employed. The periodicity of the waves within the series of acquired images allowed to resolve the excited disturbances exactly at the disturbance frequency. Thus, standard Fast Fourier Transform algorithms were used for data analysis.

3. LINEAR WAVE REGIME

The linear approach for any system is typically restricted by the amplitude of the disturbances. Unfortunately, it could not be found in the literature an ubiquitous amplitude threshold to define a linear range for the evolution of interfacial waves. In the work of Bontozoglou (1991) a transition criteria for slug initiation is given based on a weakly nonlinear analysis of the stratified flow. However, the criteria does not necessarily reflects a threshold for transition initiation rather than a limit for validity of linear theory. Thus, prior to the characterization of interfacial waves, a set of preliminary experiments were performed to ensure that excited disturbances were within the linear regime in the measurement domain.

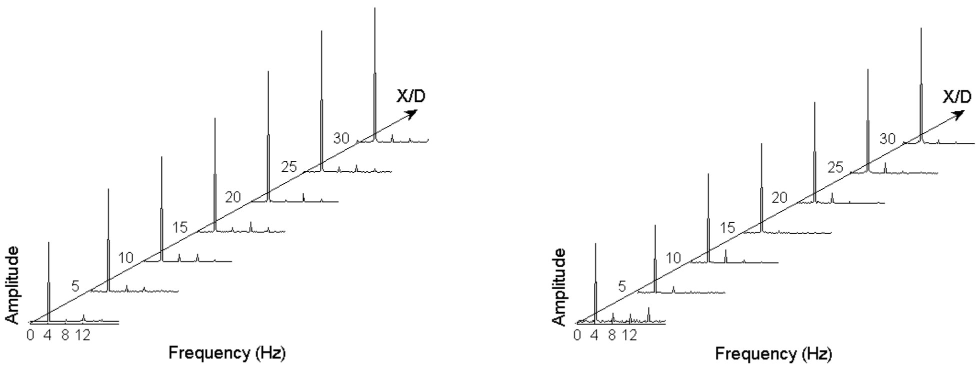
3.1 LINEARITY TEST

At first, it was necessary to define an amplitude threshold for waves to be considered as linear. For this test, the driving voltage of the oscillating paddle was varied and the resulting change in amplitude of the interfacial waves was monitored at the farthest measurement station downstream from the paddle ($\approx 40D$).

According to the results of Fig. 2, no evident amplitude threshold was observed. However, waves having amplitudes below $0.015D$ seem to scale linearly with the excitations for all cases shown in the figure. Apparently, this is a conservative threshold but it was assumed as an amplitude limit for present work in order to avoid influence of nonlinear effects on the experimental results.

The spectral evolution of interfacial waves having amplitudes lower than the threshold defined in the first set of tests were analyzed for different gas and liquid velocities. Results are depicted in Figure 3. Amplitudes in the spectra are normalized by the excited wave amplitude at the first measurement location, namely $X = 0D$. Although the spectral information is available at much higher resolution, only discrete stations are show in Figures 3. All this features facilitates a direct comparison of the results obtained for different test conditions.

The spectra of Fig. 3, show no evidence of subharmonics or harmonics of the excited wave on the spectra of oscillations at the liquid interface. In figures 3a and 3b, corresponding to cases with superficial gas velocity of $0.5m/s$, harmonics



(a) Usg=0.50m/s, Usl = 0.16m/s. (b) Usg=0.50m/s, Usl = 0.18m/s.

Figure 3: Spectral evolution of interfacial disturbances for different superficial liquid and gas velocities. Excitation frequency 4Hz

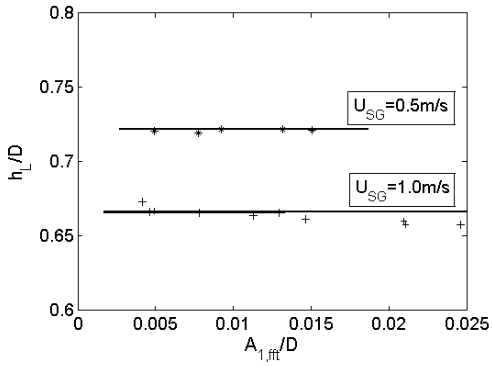


Figure 4: Variation of mean liquid height with the wave amplitude for $U_{SL} = 0.16m/s$

having low amplitudes could be found at initial stations. Further downstream they decay, or simply do not grow as the waves develop.

It is well known from hydrodynamic instability studies that nonlinear disturbances can affect the base flow (see Schmid and Henningson (2001) for a review). In a linear regime, such effect is not observed and the base flow is not modified when disturbances are present. In order to asses if the waves investigated were, indeed, within the linear regime, the mean liquid height was monitored for different forcing amplitudes. Results are depicted in figure 4. Measurements performed for different wave frequencies are combined in the same plot. According to the results, a small decrement in the mean liquid height was observed for wave amplitudes higher than $0.015D$. Amplitudes smaller than $0.15D$ induced no change in mean liquid height. This corroborate with the amplitude threshold defined according with the analysis of results from figure 2. The current findings strongly suggest that interfacial waves with amplitudes smaller than $0.015D$ are linear within the flow rates analyzed. Characteristics of these waves are detailed in the following section.

3.2 BASE FLOW AND EIGENFUNCTIONS

According to Kaffel and Riaz (2015) detailed characterization of the interfacial waves has been carried out mostly for two-phase boundary layer and shear flow problems. Channel and pipe flows are rather less explored. Up to date, most of theoretical works address the problem when both phases are laminar. Indeed, turbulent two-phase flow modeling is challenging due to interactions between turbulence and interface which can be coupled and led to a modification of the flow. Recently, Ayati *et al.* (2016) used PIV measurements to observe interaction between turbulence in the gas and interfacial waves. In the reported scenario, accurate stability predictions are rather difficult, because turbulence can actively modify the wave development. An experimental characterization of interfacial waves is important for validation of models. Characteristics such as wavenumber, celerity and wave growth are obtained and reported. Similar data for waves composed by a single Fourier mode was not found in the literature by the authors.

Measured phase evolution of the waves are shown in figure 5. Phases were extracted from the spectra of interfacial oscillations. The spatial resolution of the measurement was rather high, i.e. one pixel of the camera. In order to avoid excessive amount of data in the graph, only phases from every 120 pixel are shown. It is worth to mention that no averaging or smoothing was applied to the data. Only phase corrections of 2π and its multiples employed to account for

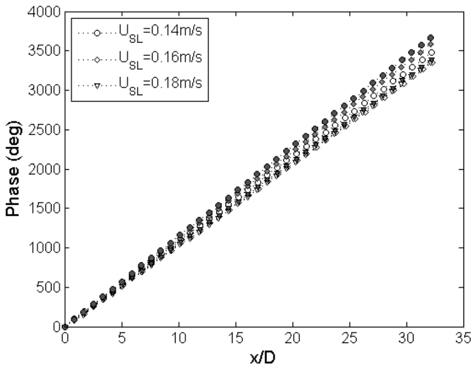
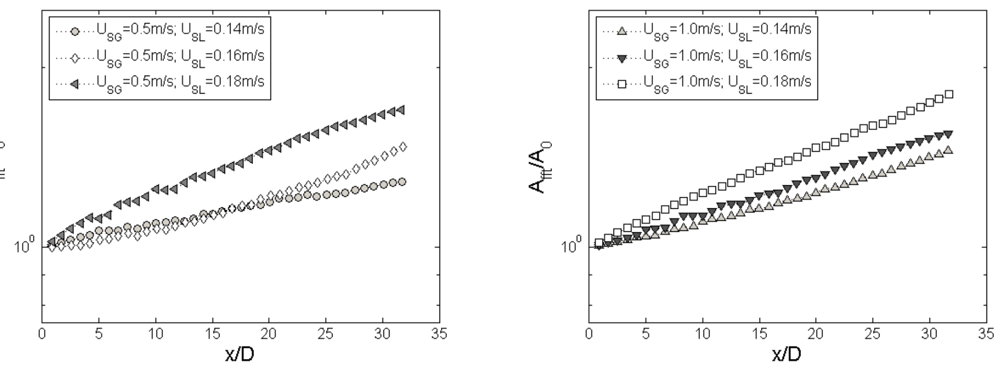


Figure 5: Phase evolution of waves for different superficial velocities and wave frequencies. Open and filled symbols correspond to superficial gas velocities of 0.5 and $1.0m/s$, respectively.



(a) Usg=0.50m/s. (b) Usg=1m/s.

Figure 6: Wave growth along pipe axis for three different flow rate combinations

complete wave cycles. The results show a linear phase variation of the waves for the whole measurement region.

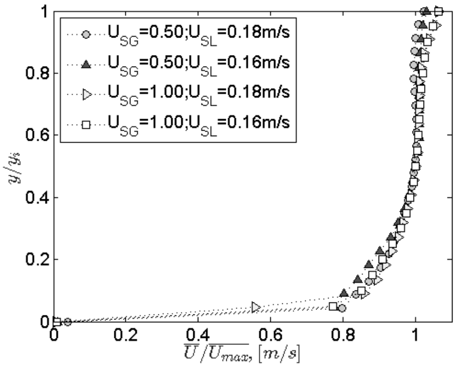
Amplitude of interfacial waves were also observed for different test conditions. Experimental results obtained for disturbances with a frequency of 4Hz are depicted in figures 6a and 6b. Similarly to the phase analysis, only points at every 120 pixels are shown in the curves of Fig 6. Experimental curves are normalized by the amplitude of the the first measurement station ($x/D = 0$). According to the figures, the amplification was stronger for increasingly higher liquid velocities. Apparently, variations in the gas flow rate had minor influence on the wave growth. This is consistent with the picture drawn from flow regime maps, such as those from the works of Mandhane *et al.* (1974); Taitel and Dukler (1976); Barnea (1987), among others. In general, those maps point out for a higher influence of the liquid velocity on the stability of smooth stratified flow. This is valid only for gas velocities remarkably lower than the transition limit to wavy or to annular flow regimes.

Curves in figures 6a and 6b show a linear amplification in a log scale. To the authors knowledge, this behavior is captured experimentally for the first time. No evidence of other mechanism than the instability of the interfacial waves was observed within the streamwise domain analyzed. Results suggest that wind shearing effects and gas turbulence are not strong enough to influence the growth of waves with frequency of 4Hz.

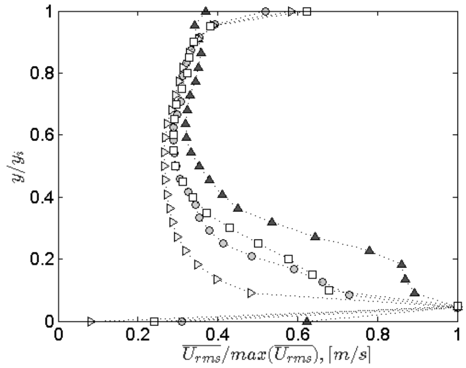
3.3 Base flow and eigenfunctions

In this section the base flow and eigenfunction profiles of interfacial waves are measured in the liquid layer using a planar PIV. Recent works of Kaffel and Riaz (2015) and Barmak *et al.* (2016), investigated the coalescence of shear and interfacial modes in a channel flow. According to Kaffel and Riaz (2015), eigenfunction profiles are not well investigated for channel flows. For pipe flows the experimental evidence of eigenfunctions related to interfacial waves are nearly absent. Thus, here the liquid portion of the eigenfunctions corresponding to interfacial instability modes were carefully measured. It is also very important to characterize the base flow and the turbulence intensity profiles. These last profiles are shown in figures 7a, 7b and 7c for mean streamwise velocity and streamwise and wall normal fluctuations, respectively.

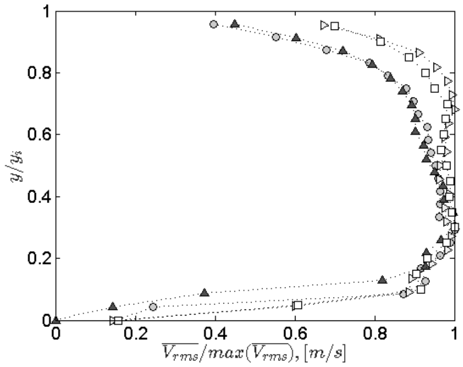
Profiles of mean flow velocity in figure 7a display a small increment of the velocity close to the interface. this is typical for liquid layers in smooth stratified flows, as observed previously in the works of Ayati *et al.* (2015) and Birvalski *et al.* (2014). According to Ayati *et al.* (2015) and Birvalski *et al.* (2014) base flow profiles of wavy flows typically exhibit a



(a) Mean velocity



(b) $U\prime$ Fluctuations



(c) $V\prime$ Fluctuations

Figure 7: Mean liquid velocity and RMS of fluctuations at low disturbance condition, i.e. A_{rms}/D below 0.01

small velocity decrement close to the interface. This is not the case here.

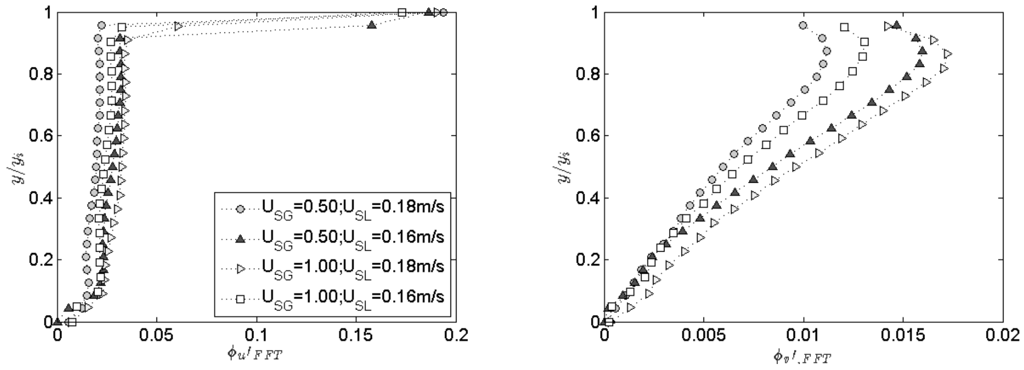
Streamwise and wall normal velocity fluctuations, depicted in figures 7b and 7c respectively, do also show qualitative similarities with results reported in the literature for smooth stratified flow (Ayati *et al.*, 2015; Birvalski *et al.*, 2014). Profiles of streamwise velocity fluctuations display higher turbulence intensities near the wall and close to the interface. Apparently, the intensity peak close to the wall is related to wall shear disturbances of turbulent flows whereas the higher intensity at the interface is linked to interfacial disturbances. To date, it is not yet clear if these two disturbances are coupled in turbulent flows due to the high intensity of fluctuations close to the wall, which can not be regarded as infinitesimal for linearization of the problem. Wall normal fluctuations illustrated in figure 7c , display high intensities in the bulk of the liquid layer. Thus, no evident separation between the inner and interfacial disturbances can be extracted from this figure. In order to shed additional light on the physics of this problem, the turbulence inner disturbances and the interfacial ones need to be analyzed separately.

One of the main advantages of phase locked measurements combined with controlled excitation of disturbances is the capability of extraction of the coherent oscillations from the noisy signals. To this end simple spectral decomposition is enough to enable extraction of coherent part of the signal. Thereby, portions of the turbulence intensity profiles related to the wave frequency were analyzed separately. These fluctuations corresponded to the eigenfunctions of the interfacial waves.

The eigenfunctions of streamwise and wall normal fluctuations are shown in figures 8a and 8b for waves with frequency of 4Hz. In general, shapes of the eigenfunctions of figure 8 were not modified for the tested conditions. Profiles of u' display a peak at the interface, but their amplitude nearly vanish at the bottom wall. The current findings support the explanation given in the last paragraph for the nature of the two peaks in the profile of streamwise fluctuations. According to the figure 8a, the lower peak is, indeed, not related with the interfacial mode. In figure 8b the eigenfunction of v' display a peak slightly below the interface. The picture display qualitatively similar features in comparison with the eigenfunctions found in the works of Kaffel and Riaz (2015) and Barmak *et al.* (2016) for laminar flows.

4. CONCLUSION

The concepts of shadow technique, Particle Image Velocimetry, controlled disturbances and phase locked image acquisitions were applied to investigate the evolution of interfacial waves in turbulent gas-liquid stratified flow. The experimental results obtained show high degree of reproducibility which enabled to track the evolution of excited disturbances along



(a) $\Phi(U\prime)$ (b) $\Phi(V\prime)$

Figure 8: Eigenfunctions of 4Hz waves with amplitudes smaller than A_{rms}/D =0.015.

the pipe. Measurements were carried out at flow rates close to the transition from smooth stratified to intermittent flow. The results reported here can help to shed some additional light about how the two-phase stratified pipe flow compares with other two phase shear flows such as boundary layer and channel flows.

The work focused on the characterization of interfacial waves in the linear regime of their development. Therefore, only waves having very small amplitudes were investigated. The amplitude threshold for assuming waves as linear ones, was obtained experimentally. Preliminary tests with waves excited with different initial amplitudes allowed to estimate qualitatively the amplitude threshold for linear regime of wave development. Within the range of tested parameters, amplitudes smaller than 1.5% of the pipe diameter displayed features of linear waves. It is important to mention, that no clear and well defined threshold was observed. The limiting amplitude was taken from the worst situation observed, when non-linear features were first observed in the experiments. For the majority of tested situations, this threshold was very conservative. Nevertheless, no significant harmonics and subharmonics were noticed in the signal spectra for waves with amplitudes smaller than 1.5% of the pipe diameter. In addition, the mean liquid height was unaffected by the presence of waves with small amplitude.

Another interesting result observed in the experimental data, was the rather linear phase evolution of the interfacial waves. According to the current findings no influence of turbulence in the liquid and gas phases was observed. The results clearly showed that dispersion characteristics of the waves remained unaffected even in the presence of highly noisy environment. It is also worth to mention that the same statement might be not true for highly sheared flows, i.e. high gas flow rates.

The part of the eigenfunctions of the interfacial waves were extracted from the flow fluctuations within the liquid layer. To the knowledge of the authors, this is the first time that such data is reported in the literature. The profiles show that interfacial modes are nearly independent of inner modes for the range of the current investigation. The results are in qualitative agreement with the works of Kaffel and Riaz (2015) and Barmak *et al.* (2016), even though the flow regime is different. For low levels of liquid or for pipes with small diameters the situation might be modified and interaction between modes can play a role.

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