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Slug Frequency Measurement Techniques in Horizontal Gas–Liquid Flow

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Nomenclature

D = pipe diameter, m
d = bubble diameter, m
f = frequency, Hz
f_M = mean slug frequency, Hz
f_S = spectral component, Hz
J_g = gas superficial velocity, m/s
J_l = liquid superficial velocity, m/s
P_g = phase density function
P_g^* = filtered phase density function
s = sampling rate, Hz
T = time series duration, s
T_g = gas bubble duration, s
T_i = ith slug unit duration, s
t = time, s
y = vertical distance from pipe top wall, m
z = distance from pipe inlet, m

I. Introduction

THE cocurrent flow of gas and liquid has great importance in a huge variety of devices, including aerospace and microgravity systems. In many such applications, the so-called horizontal intermittent flow is encountered. This flow regime is characterized by an intrinsic unsteadiness, due to the alternating of liquid slugs filling the whole pipe cross section and of regions in which the flow consists of a liquid layer and a gas layer. The liquid slug together with one of the adjacent stratified regions is sometimes called a cell or slug unit. The intermittent behavior causes high pressure and flow rate fluctuations, so that an extremely careful design of the pipeline components (valves, orifices, etc.) is required. Moreover, the low-frequency values of the slugs (few hertz) may be in resonance with the characteristic frequency of the pipeline itself, causing serious damages if not taken into account. Thus, the correct prediction of slug frequencies is essential in all practical applications of gas–liquid horizontal flow. From another point of view, the slug frequency (or, alternatively, the slug length) is an input parameter of all of the slug flow models existing in the literature, such as those by Fabre and Linè[1] and De Henau and Raithby.[2]

During the past few decades much effort has been devoted to the investigation of slug frequency. Unfortunately, the results obtained were not in proportion, both because there is no theoretical description of this phenomenon and because the slug frequency shows no clear relationship with other quantities such as the void fraction or the pressure gradient. Most of the existing correlations are essentially empirical and express the average slug frequency as a function of the superficial velocities of the two phases, such as the correlation by Gregory and Scott.[3] Attempts to form theoretical predictions have been made, for example, by Taitel and Dukler[4] and Tronconi,[5] but their models are not applicable under several flow conditions.

In the absence of a complete mathematical description of slug flow, slug frequency must be estimated from statistical measurements. The methods commonly used consist in simply counting the number of slugs per unit time, as proposed by Hubbard,[6] or in taking the reciprocal of the mean time delay between two consecutive slugs, as proposed by Ferré.[7] The two definitions, which are perfectly equivalent to each other as one can easily verify, provide for a mean slug frequency value. A completely different approach to slug frequency measurements is represented by the Fourier analysis of the optical probe output. In fact, the power spectral density (PSD) maximum indicates the most important harmonic component, which is not necessarily the same as the mean frequency estimated with the earlier mentioned methods. Moreover, the PSD may exhibit additional peaks, corresponding to the frequencies of other meaningful harmonic components. A comparative analysis of the two different methods for measuring slug frequency is presented here.

II. Experiments

The experiments were carried out on air–water flow at atmospheric pressure and temperature, in a horizontal pipe of 0.08 m i.d.; the water mass flow rates were 3, 4.5, 7, and 10 kg/s, whereas the gas fraction of volume flow ranged from 0.2 to 0.8. Correspondingly, the superficial velocities were 0.6, 0.9, 1.4, and 2 m/s for the liquid and ranged from 0.3 to 8 m/s for the air. The experimental facility is schematically shown in Fig. 1.

Three single fiber optical probes were introduced into the test section at 96, 101, and 104 diameters from the pipe inlet, where the flow could be considered fully developed.[8] These probes have a conical tip, which is sensitive to the refractive index of the surrounding medium, so that the output is a binary signal, which is equal to 1 if the tip is surrounded by air and to 0 if it is surrounded by water (the so-called phase density function). This kind of instrumentation is well known,[9,10] and, although extremely delicate, it provides for highly accurate local measurements as compared with other instruments.[11]

The probes were moved along the vertical diameter of the pipe cross section by micrometric screws. The phase density function $P_g(t)$ was measured at five points uniformly distributed in the upper part of the pipe (0.05, 0.1, 0.15, 0.2, and 0.25 i.d. from the top). The time series duration and the sampling rate were set based on previous measurements.[8] In particular, the duration of each time series was 400 s to obtain steady local void fraction values; the sampling rate was adjusted to 2 kHz, so that the instrument could distinguish small bubbles or drops.

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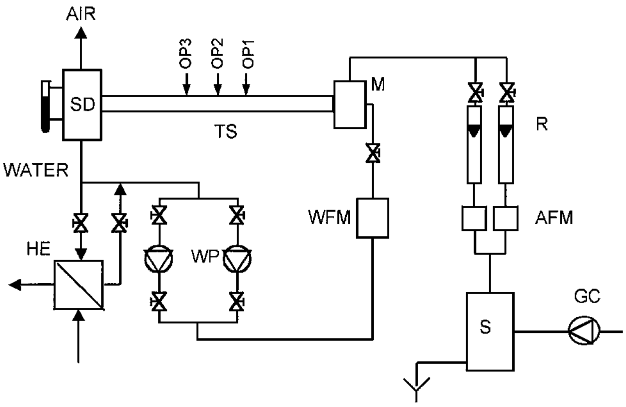

Fig. 1 Experimental facility: water pumps (WP), air compressor (GC), centrifugal separator (S), air (AFM) and water (WFM) flow meters, air rotameters (R), mixer (M), test section (TS) with the optical probes (OP1,2,3), and separation drum (SD); heat exchanger (HE) is used to remove dissipated heat.

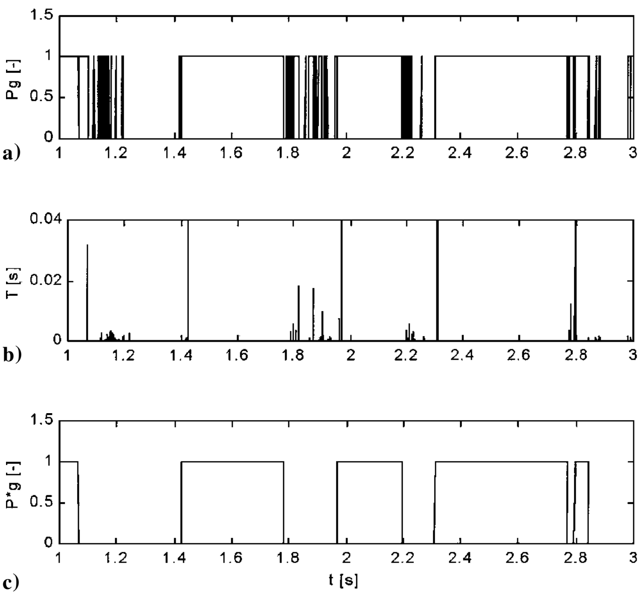

Fig. 2 Signal processing procedure where $J_l = 1.4$ m/s, $J_g = 0.34$ m/s, and $y/D = 0.15$: a) measured phase density function time series, b) converted into a series of impulses proportional to the duration of the gas bubbles, and c) smallest bubbles cut off and slug units sequence reconstructed.

When positioned into the flow above the liquid layer, the optical probes easily allow slug detection because, when the liquid fills the pipe, the phase density function drops to zero. The noise affecting such a signal is represented essentially by the small gas bubbles which, especially for high gas flow rates, are entrained in the liquid slug. Because the characteristic dimension of these bubbles is about 10^2 times smaller than that of large gas pockets,[12] noise was reduced by suppressing the trace of gas enclosures with a smaller size than the overall average size, as shown in Fig. 2. The filtered phase density function $P_g^*(t)$ was then resampled at 10 Hz.

The P_g^* time series allow calculating the slug frequency either by the slug-counting method or by means of the Fourier analysis; in the latter case, the PSD was calculated by the standard Welch method (see Ref. 13), with a frequency resolution of 0.05 Hz. In particular, in each of the five points of the vertical diameter defined earlier, the frequency was calculated as the average of the three values obtained from the probes placed at $z/D = 96$, 101, and 104. The same averaging procedure was used to calculate the PSD of the P_g^* time series. Because both the mean slug frequency and the frequency spectra are insensitive to the choice of the probe position along the vertical diameter,[14] ensemble averaging was repeated over the values obtained in the five positions already defined.

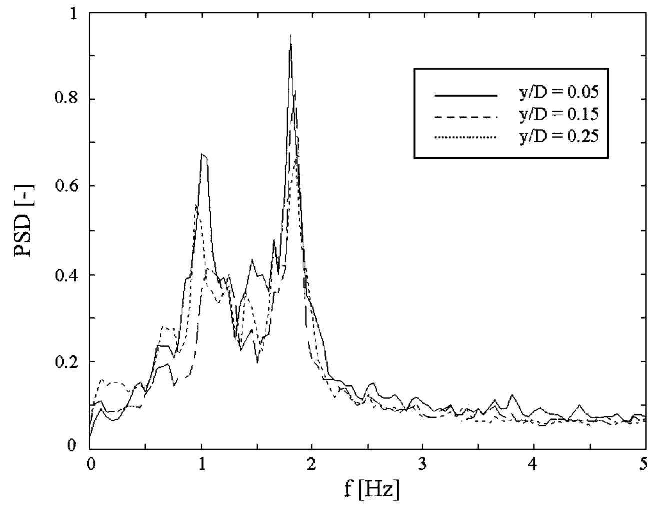

Fig. 3 Example of bimodal frequency spectrum; $J_l = 1.4$ m/s and $J_g = 0.44$ m/s.

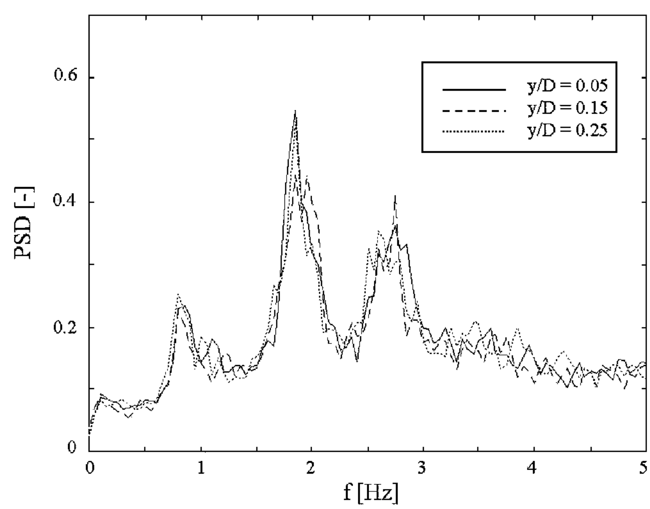

Fig. 4 Example of trimodal frequency spectrum; $J_l = 2$ m/s and $J_g = 2.74$ m/s.

III. Results and Discussion

The results of the Fourier analysis reveal some interesting details of the slug frequency behavior. In fact, for $J_l > 1$ m/s, under certain flow conditions, the phase density function spectra may show two or three main harmonic components, corresponding to three well-distinguished frequency values. Figures 3 and 4 show an example of a bimodal spectrum and of a trimodal one, respectively. Figures 3 and 4 also show that, for assigned flow conditions, the existence of multiple harmonic components does not depend on the position in which the measurement is made, so that it must be related to the slug dynamics and not to the smaller structures that may be locally observed, such as small gas bubbles or waves that do not fill the whole pipe cross section. Such multiple characteristic frequencies suggest that slug dynamics is more complex than a simple periodic motion with a statistically distributed but single frequency. Regardless of the frequency spectrum, the slug-counting method originally proposed by Hubbard[6] always returns one value for the slug frequency; therefore, it does not allow detecting multiple characteristic frequencies.

The slug frequency measurements performed according to the two methods are consistent with each other, as shown in Fig. 5, which shows the two frequencies f_M and f_S with respect to the gas superficial velocity, for different values of the liquid superficial velocity. In particular, for low liquid superficial velocities ($J_l < 1$ m/s) the two methods return almost the same value for the slug frequency, so that they can be considered equivalent. For a low superficial velocity of the gas, there is a single slug frequency value; as J_g grows,

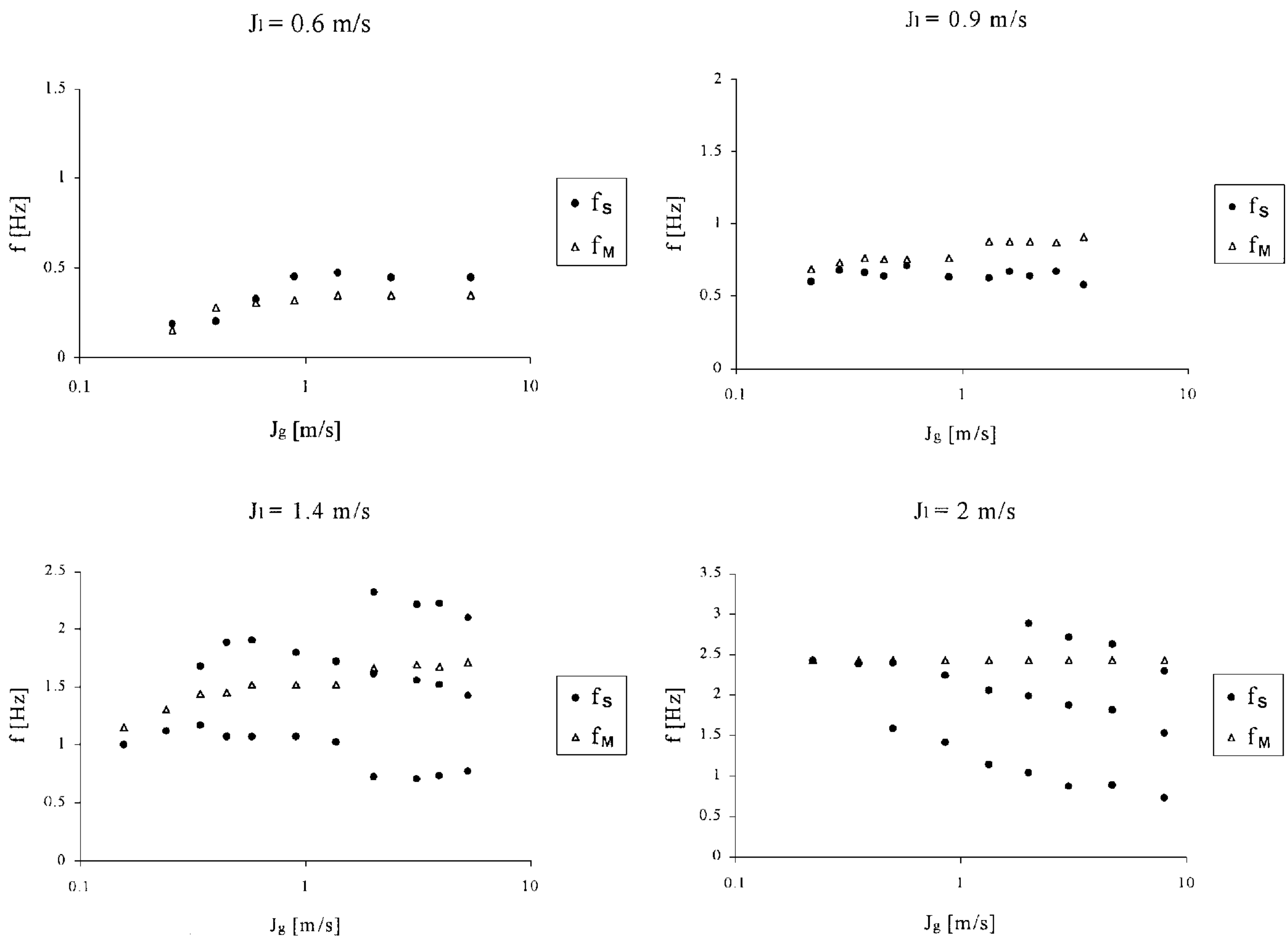

Fig. 5 Comparison between results of the Fourier analysis and those of the slug-counting method.

the power spectra indicate the existence of more harmonic components at different frequencies. Bimodal spectra can be observed in the range 0.5 m/s $< J_g <$ 2 m/s, whereas trimodal spectra appear for $J_g >$ 2 m/s, so that the frequency plot shows two bifurcations.

IV. Conclusions

The analysis of the classical method for liquid slugs mean frequency measurements leads to the conclusion that it cannot be considered a completely reliable tool: In fact, although this method estimates the mean frequency with a precision of $\pm 1\%$ (Ref. 14), it cannot take into account the existence of multiple harmonic components. Moreover, the mean frequency value turns out to be affected both by the sampling rate and by the signal filtering, especially if it is calculated on the basis of local measurements.[12,14] Thus, correlations based on mean frequency data cannot adequately represent the slug dynamics. The estimation of slug frequency from the PSD of the phase density function time series provides a better insight of slug flow: In fact, even if the frequency is estimated with a precision of $\pm 5\%$ (Ref. 14), this method allows distinguishing all of the most important harmonic components, corresponding to different characteristic frequencies of liquid slugs.

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