EXPERIMENTAL STUDY ON THE MEASUREMENT OF TWO-PHASE FLOW RATE USING PIPE VIBRATION

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Abstract. *The two-phase flow of gas and liquids is usually encountered in piping systems and process plant equipment in the production of oil and gas. The vibration excited by the two-phase flow is known to be related to the flow momentum variation due to the presence of phases with distinct densities. Fluctuating forces can arise in flow-turning piping elements like bends, elbows and tees producing severe piping vibrations. This work presents an experimental investigation on the relationship between piping vibration and the two-phase flow rate. Measurements of vibration were performed in pipe sections of an air-water loop subjected to a wide range of flow rates of air and water. Correlations between the root mean square of pipe acceleration and the superficial velocity of the two-phase flow were obtained for different void fractions. Based on the experimental results a method for the measurement of the two-phase flow rate of liquid and gas is proposed.*

Keywords*: Two-phase flow; Flow rate measurement; Pipe vibration*

1. INTRODUCTION

The internal two-phase flow of liquid and gas is a common source of pipe vibration in piping systems of oil and gas production and in the nuclear industry. The two-phase flow vibration excitation mechanism is known to be related to the flow momentum variation due to the presence of phases with distinct densities. Particularly in the production of oil and gas, many cases of excessive vibration in piping systems have been noticed by the authors (Gama *et al*., 2006). The two-phase flow dynamic forces acting in some pipe elements like bends and elbows can produce high levels of vibration. A detailed investigation on fluctuating forces caused by the two-phase flow can be found in the works conducted by Riverin and Pettigrew (2007) and Riverin *et al* (2006). Through an experimental study in an air-water loop, Riverin and Pettigrew (2007) concluded that the pipe vibration is due to a resonance phenomenon between periodic momentum flux fluctuations of two-phase flow and the first modes of vibration of the piping system. The predominant frequency of excitation force was observed to increase proportionally to the flow velocity.

With the purpose of correcting vibration in existing piping systems and identify the characteristics of the two-phase flow induced vibration, a field investigation was conducted by the authors of the present work in offshore platforms of production of oil and gas. The results of measured vibration in piping systems conveying oil and gas showed a strong correlation between the two-phase flow rates and piping vibration. This evidence motivated the present work where an experimental study in pipe sections of an air-water loop has been performed to obtain the relationship between the signal of vibration transducers mounted in pipe elements and the flow rates of air and water. The main aim of this investigation is to verify the possibility of using the pipe vibration response to measure the two-flow rates of liquid and gas, providing a low cost non intrusive method that could be easily implemented also in existing piping systems. In addition, the proposed method would offer the possibility of a nearly real time measurement of two-phase flow rate.

As the separation of phases is a necessary condition in the petroleum industry, the measurement of two-phase flow rate of oil and gas is usually performed by separating the mixture and using conventional devices for measuring single-phase flow. However, the measurement of two-phase flow rate in an online and continuous manner is a desirable condition as this would allow for the real time monitoring of the wheel production and condition.

Evans *et al.* (2004) have performed an experimental investigation on the flow rate measurement based on the turbulent single phase flow induced pipe vibration and concluded that there is a strong deterministic relationship between the standard deviation of the pipe acceleration, obtained with an accelerometer mounted on the surface of a pipe, and the flow rate. Although the tests were restricted to single phase flow, the authors noticed that in turbulent flow the standard deviation of the accelerometer signal increased with flow rate and vary in a quadratic manner. In the present work, the authors investigated the correlation between piping vibration and the two-phase flow rates of air and water. To obtain higher vibration levels, an air-water loop with pipe test sections composed of straight pipes and bends were employed. The two-phase flow dynamic forces acting on the bends increase the pipe vibration and consequently improve the sensitivity of the method to variations in the flow rates. Pipe vibration response was measured with accelerometers mounted to the pipe. The root mean square (RMS) and the standard deviation were calculated from the pipe acceleration data and correlated to the mixture superficial velocity of air and water for various flow conditions. Each test was performed with a different volume fraction that was kept constant while varying the mixture superficial velocity. Piping vibration was observed to increase with flow velocity. Second order polynomials were fitted to the experimental data obtained in the tests. An equation relating the RMS pipe acceleration with the two-phase mixture superficial velocity was obtained for various volume fractions of air and water. To determine the two-phase flow rates it is also necessary to known the two-phase volume fraction of phases. A method for the measurement of volume fractions based on the variation of piping natural frequencies is also proposed and demonstrated. The preliminary results indicate the possibility of developing a low cost noninvasive method for the measurement of two-phase flow rates by combining the techniques proposed here.

2. EXPERIMENTAL APPARATUS

A schematic diagram of the air-water flow loop is shown in Figure 1. The air system consists of a compressor, manually operated flow control valves and rotameters for the measurement of air flow rates. The water system consists of a reservoir, a centrifugal pump, a by-pass section, manually operated flow control valves and rotameters for the measurement of water flow rates. The test sections are made of acrylic pipes with inner diameter *Di = 25.4 mm* and outside diameter *Do = 31.8 mm*.

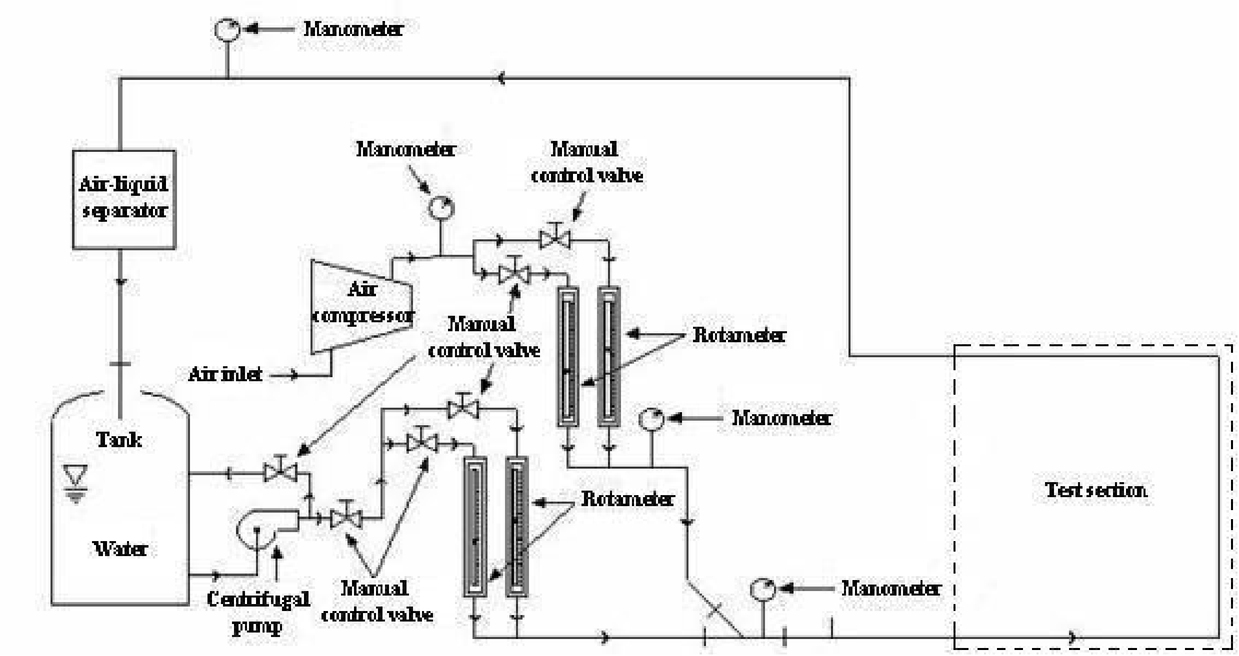

Figure 1. Schematic diagram of the air-water loop.

In order to achieve higher vibration levels generated by the two-phase flow, pipe sections with bends were employed. Figure 2 shows the geometry of the test sections: a L shaped pipe composed of a bend with radius of curvature *R/D = 3* and straight legs and a U shaped pipe made with two bends (*R/D* = 3) connected by straight pipes. Each pipe element was tested separately. The test sections were placed in the horizontal plane to obtain the out of plane vibration in the case of the L-pipe, and the out of plane and the in plane vibration in the case of the U-pipe. Before entering the test section, air and water are mixed and pass through a straight pipe with approximately $70\ D_i$ length to obtain a developed flow (approximately $110\ D_i$ length before entering the first bend). After flowing through the test section, air and water are separated in a separator. The water returns to the reservoir and the air is released to the atmosphere. The acrylic pipe section is anchored to a stiff framed steel structure through steel blocks in the points shown in Figure 2. Vibration isolators were used in the compressor and centrifugal pump to avoid the transmissibility of vibration to the test section.

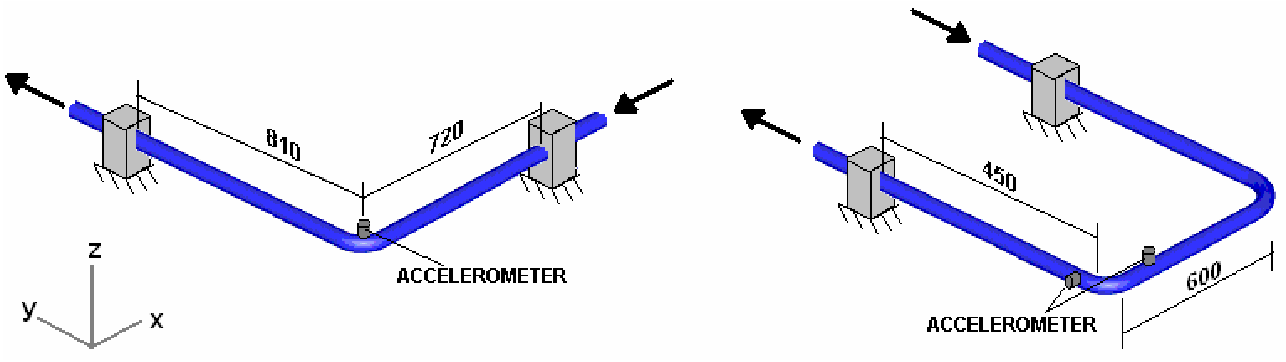

Figure 2. Pipe elements used in the experiments. Dimensions in millimeters.

3. TWO-PHASE FLOW CONDITIONS

The parameters used to specify the two-phase flow conditions used in the experiments were the mixture velocity V given by the sum of water superficial velocity V_L and the air superficial velocity V_G, and the volume fraction of air C_G:

$$V = V_L + V_G \tag{1}$$

$$C_G = \frac{V_G}{V} \tag{2}$$

The superficial velocities V_L and V_G are defined as

$$V_L = \frac{Q_L}{A} \quad \text{and} \quad V_G = \frac{Q_G}{A} \tag{3}$$

where Q_L and Q_G are the volumetric flow rate of water and air respectively, and A is the pipe cross sectional area. The flow conditions used in the experiments are depicted in Table 1. The flow rates of air were varied from 0.88 to 16.8 m^3/h and the flow rates of water varied from 0.18 to 5.30 m^3/h. According to the experimental flow pattern map for air and water flowing through a straight pipe in the horizontal position obtained by Mandhane *et al.* (1974), most of the flow conditions in Table 1 correspond to the slug flow regime. This is in agreement with the flow patterns observed by the authors during the experiments.

Table 1. Two-phase flow conditions.

Number	Mixture Superficial Velocity (m/s)	Air volume fraction (%)
	V (m/s)	C_G
1	1	50
2	2	50
3	3	50
4	4	50
5	5	50
6	6	50
7	1	60
8	2	60
9	3	60
10	4	60
11	5	60
12	6	60
23	3	80
24	4	80
25	5	80
26	6	80
27	7	80
28	8	80
29	1	90
30	2	90
31	3	90
32	4	90
33	5	90
34	6	90

Table 1(Cont.). Two-phase flow conditions.

13	1	70
14	2	70
15	3	70
16	4	70
17	5	70
18	6	70
19	7	70
20	8	70
21	1	80
22	2	80
35	7	90
36	8	90
37	2	95
38	3	95
39	4	95
40	5	95
41	6	95
42	7	95
43	8	95
44	10	95

4. VIBRATION MEASUREMENTS

The air-water flow induced vibration was measured with accelerometers mounted on the acrylic pipe as shown in Figure 2. Out of plane vibration were measured on the L-pipe, while both in-plane and out of plane vibration were measured simultaneously on the U-pipe. The data from the accelerometers were recorded on a PC based data acquisition system and on a dynamic signal analyzer. For each two-phase flow condition described in Table 1, piping vibration was measured during 50 seconds using a sample rate of 400 samples per second and recorded on the PC data acquisition system. The 50 seconds data acquisition time was chosen based on the pipe vibration behavior and flow unsteadiness. This period of acquisition should be sufficiently large to present a vibration data representative of the two-phase flow condition.

5. VIBRATION RESPONSE

The excitation mechanism of piping vibration due to the two-phase flow is a combination of narrow-band random and periodic forces components (Riverin and Pettigrew, 2007). The vibratory response due to the two-phase flow excitation also depends on pipe geometry, pipe material and boundary conditions. If the pipe natural frequency is within the two-phase flow band of excitation frequency, a resonant behavior is expected to occur for some flow conditions and the relationship between pipe vibration and mixture superficial velocity would change locally in the range of flow velocity where resonance occurs.

As an example of pipe response due to the two-phase flow excitation, Fig. 3 shows the in-plane vibratory response (acceleration measured in the x direction) of the U-pipe for different volume fractions of air and different mixture superficial velocities. One can notice that pipe vibration has a random behavior with periodic components, in addition, an increase of acceleration amplitude due to increasing mixture velocity is observed. Note also that the peaks of acceleration due to the passage of the slug through the pipe bends, observed more clearly for $C_G = 90\%$, increase in amplitude and frequency with the mixture superficial velocity.

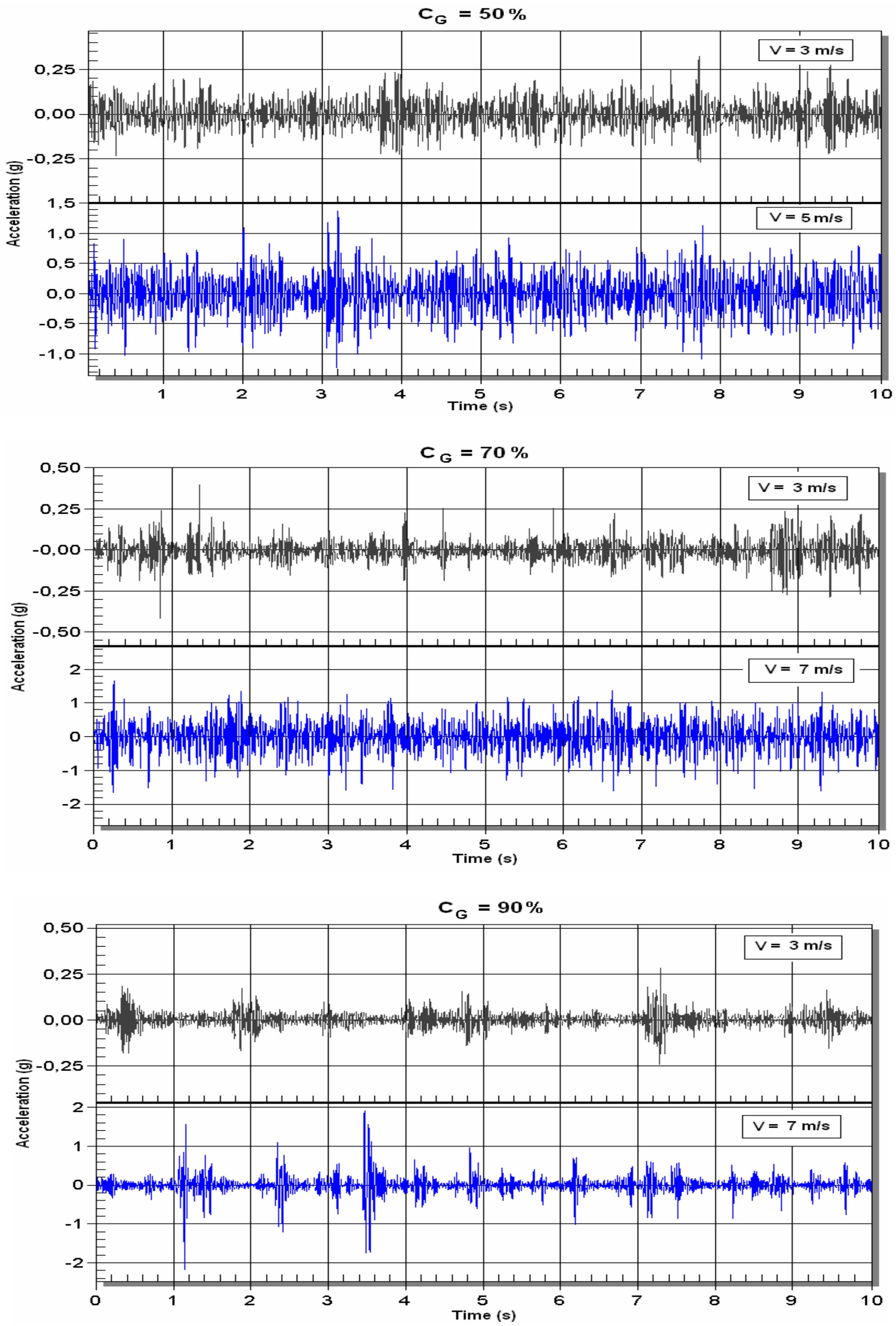

Figure 3 . Examples of in-plane vibration response of the U-pipe (acceleration in the x direction).

6. RELATIONSHIP BETWEEN PIPE VIBRATION AND THE TWO-PHASE FLOW

The root mean square and the standard deviation were calculated from the acceleration data recorded for each test performed according to the flow conditions presented in Table 1. The calculations were performed using all the data collected during the 50 s time of acquisition.

6.1. L-pipe

Figure 4 shows the variation of the out of plane RMS acceleration in function of the mixture superficial velocity for different volume fractions of air. The acceleration was measured with an accelerometer placed on the bend of the L-pipe as shown in fig. 2. The points indicate the RMS acceleration calculated from the experimental data, and the continuous line the second order polynomial fitted to the calculated values from the experimental data obtained in tests with the same volume fraction of air.

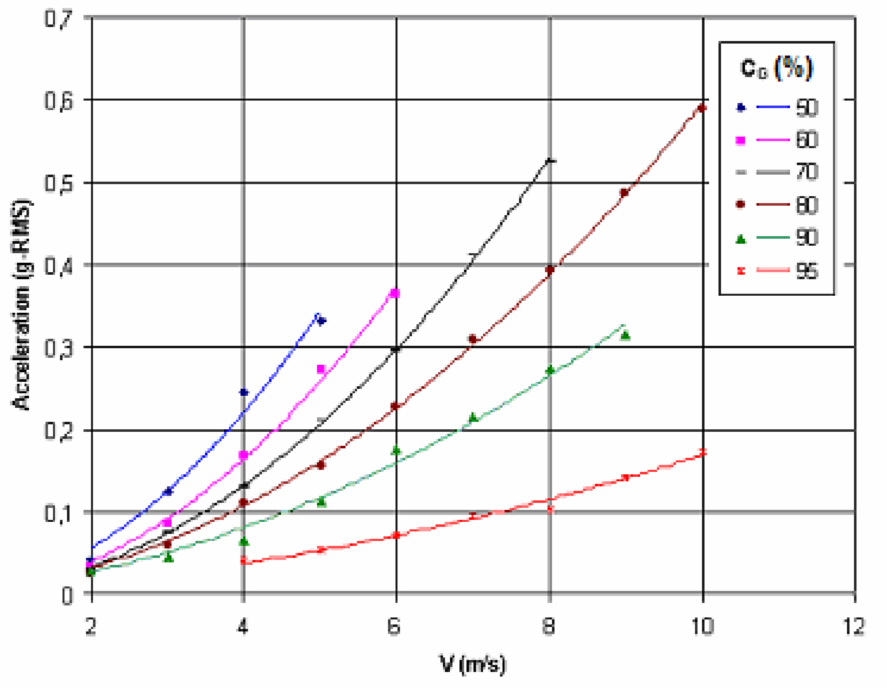

Figure 4. Out of plane RMS acceleration in function of mixture velocity for different volume fractions of air – L-pipe.

For a given volume fraction of air one can note that the acceleration increases with the mixture superficial velocity in a quadratic manner. The second order polynomials and values of the goodness-of-fit measure R^2 corresponding to each curve fitted to the data is shown in Table 2. The point corresponding to zero flow and zero acceleration was included to the experimental data to obtain the polynomials.

Table 2. Polynomials fitted to the data and values of the goodness-of-fit R^2 for the L-pipe.

C_G (%)	Equations	R^2
50%	$a_{RMS} = 0{,}0135V^2 + 0{,}0012V$	0,9799
60%	$a_{RMS} = 0{,}0106V^2 - 0{,}0014V$	0,9963
70%	$a_{RMS} = 0{,}0083V^2 - 0{,}0001V$	0,9995
80%	$a_{RMS} = 0{,}0054V^2 + 0{,}005V$	0,9993
90%	$a_{RMS} = 0{,}0033V^2 + 0{,}007V$	0,9900
95%	$a_{RMS} = 0{,}0013V^2 + 0{,}0043V$	0,9847

6.2. U-pipe

Figures 5 and 6 show the variation of the out of plane and the in-plane RMS acceleration in function of the mixture superficial velocity, respectively, obtained in tests with different volume fractions of air. The positions of the accelerometers placed on the U-pipe are shown in Fig. 2. The points indicate the RMS acceleration calculated from the experimental data, and the continuous line the second order polynomial fitted to the calculated values from the experimental data obtained in tests with the same volume fraction of air.

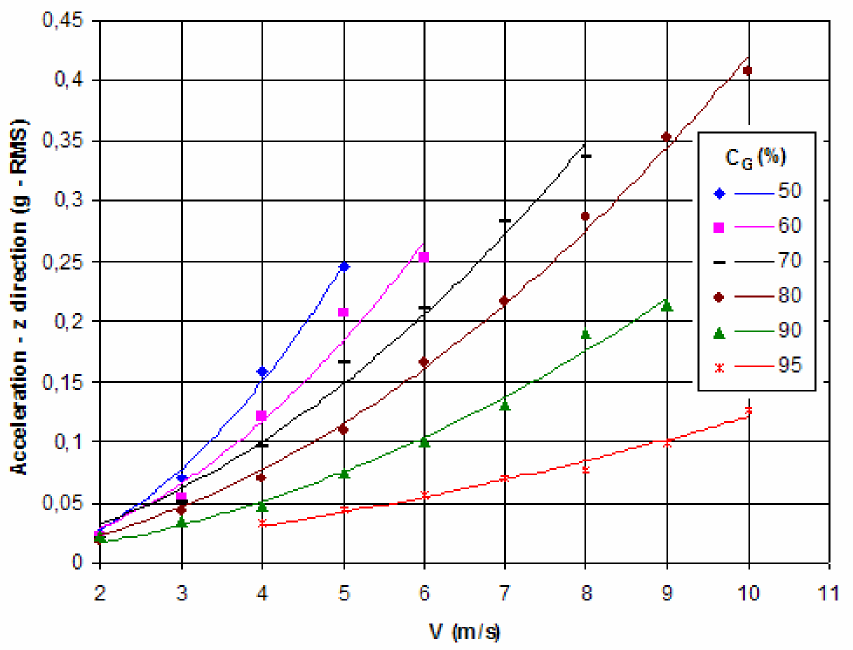

Figure 5. Out of plane RMS acceleration in function of mixture velocity for different volume fractions of air – U-pipe.

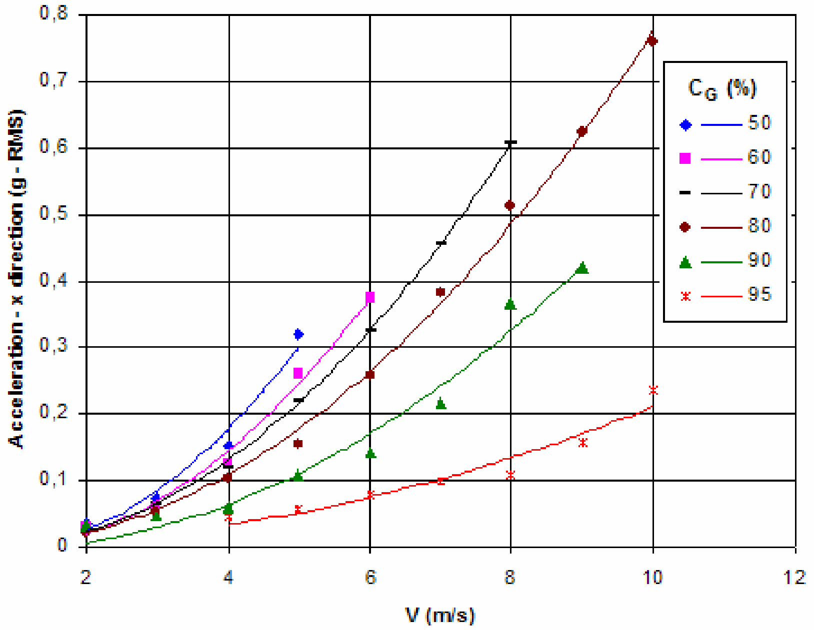

Figure 6. In-plane RMS acceleration in function of mixture velocity for different volume fractions of air – U-pipe.

For a given volume fraction of air one can note that the acceleration increases with the mixture superficial velocity in a quadratic manner, similar to the results obtained for the L-pipe. Higher levels of vibration are observed for the in-plane acceleration due to the component of fluctuation forces in the *x* direction that arise in the bends due to the flow momentum variation. The second order polynomials and the values of the goodness-of-fit measure R^2 corresponding to each curve fitted to the data are shown in Tables 3 and 4 for the in-plane and the out of plane acceleration response of the U-pipe, respectively.

Table 3. Polynomials fitted to the data and values of the goodness-of-fit R^2 for the U-pipe in-plane vibration.

C_G (%)	Equations	R^2
50%	$a_{RMS} = 0{,}0161V^2 - 0{,}0204V$	0,9692
60%	$a_{RMS} = 0{,}0132V^2 - 0{,}0172V$	0,9872
70%	$a_{RMS} = 0{,}0109V^2 - 0{,}011V$	0,9987
80%	$a_{RMS} = 0{,}0085V^2 - 0{,}007V$	0,9970
90%	$a_{RMS} = 0{,}0063V^2 - 0{,}0093V$	0,9750
95%	$a_{RMS} = 0{,}0022V^2 - 0{,}0008V$	0,9398

Table 4. Polynomials fitted to the data and values of the goodness-of-fit R^2 for the U-pipe out of plane vibration.

C_G (%)	Equations	R^2
50%	$a_{RMS} = 0{,}0118V^2 - 0{,}0096V$	0,9947
60%	$a_{RMS} = 0{,}0075V^2 - 0{,}0008V$	0,9824
70%	$a_{RMS} = 0{,}0046V^2 + 0{,}0067V$	0,9920
80%	$a_{RMS} = 0{,}0038V^2 + 0{,}0039V$	0,9974
90%	$a_{RMS} = 0{,}0023V^2 + 0{,}0034V$	0,9902
95%	$a_{RMS} = 0{,}0008V^2 + 0{,}00468V$	0,9804

In the range of volume fractions presented in Fig. 4 to 6, it is observed that for a same mixture velocity, the acceleration decreases when the volume fraction of air is increased. However, the opposite is observed for lower volume fractions of air ($C_G = 0$ *to* 40%, results not shown here). This behavior would obviously be expected as piping vibration is reduced when the flow condition approaches the single phase. The highest levels of vibration usually occur for intermediated values of volume fraction. The standard deviation of pipe acceleration was also determined and correlated to the two-phase flow mixture velocity. A quadratic relationship was also observed. The results are not shown here due to the lack of space.

The results present a strong correlation between the RMS acceleration and the mixture velocity; however, to obtain the volumetric flow rates of air and water it would be necessary to determine the volume fraction of the phases. Although procedures developed to measure the volume fraction could be used, a method also based on the pipe vibration response to determine the volume fractions was investigated in this work.

7. MEASUREMENT OF VOLUME FRACTION

The procedure investigated here to obtain the volume fractions of the phases in a two-phase flow is based on the variation of pipe natural frequencies due to changes in the volume fractions of air and water. The method consists in exciting a pipe conveying the two-phase flow with a broad-band excitation force and to determine the pipe frequency response for different volume fractions. Next, comparisons between the pipe frequency response functions are performed and the changes in the natural frequencies are correlated to the changes in the volume fraction.

The preliminary experiments were performed in a straight pipe 500 mm length clamped in both ends, placed in the horizontal position and submitted to different flow conditions. Diameters and material of the pipe are the same of the pipe used in the preceding experiments. The pipe was excited by a random force in the range of 0 to 1000 Hz applied by an electromagnetic actuator. Pipe vibration response in the vertical and horizontal directions was measured with accelerometers. A dynamic signal analyzer was used to obtain the averaged frequency response function of the accelerometers signal. The pipe frequency response was measure for the pipe conveying the two-phase flow with volume fractions varying from 0 to 100%, i.e., the conditions of single phase of water and single phase of air were also employed. The same mixture velocity was employed in the tests.

A finite element modal analysis using the commercial finite element program ANSYS^{TM} was also performed to verify the pipe natural frequency sensitivity to mass change. The analyses were made for a pipe containing water with no net flow rate. In order to capture the effect of a contained fluid in a modal analysis it was preferred to modify the structural element SOLID186 to model the water. A comparison between the experimental results and the finite element method (FEM) analyses is shown in Fig.7. The results show the variation of the natural frequency corresponding to the second pipe vibration mode. The results in Fig. 7 are in good agreement besides the simplified finite element analyses. Therefore, by monitoring the changes in the pipe natural frequencies one can determine the volume fractions and the corresponding equation relating the RMS acceleration with the mixture velocity (Tables 2 to 4).

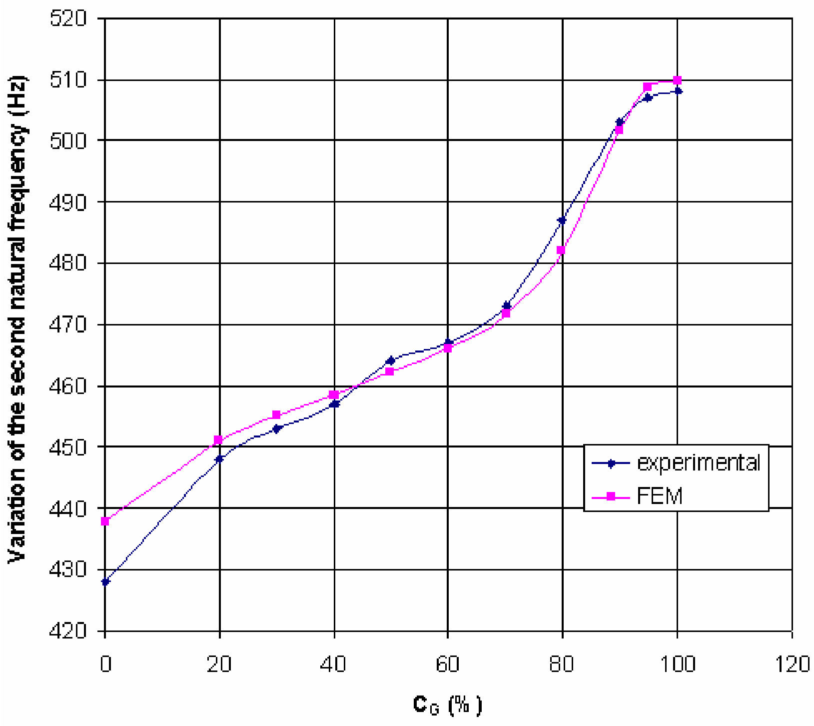

Figure 7. Variation of the second pipe natural frequency in function of volume fraction of air.

The variation of the second lowest natural frequency was chosen based on the analysis of the frequency spectrums of piping vibration obtained for different volume fractions. It was observed that the peak in the frequency spectrum corresponding to the second natural frequency presented a variation in frequency due to changes in the volume fraction that could be more clearly detected than the frequency variation observed in the first and third pipe natural frequencies.

Table 5. Material properties of pipe used in the FEM analyses.

Acrylic properties	Value
Young's modulus (GPa)	2,4
Poisson's ratio	0,35
Density (kg/m³)	1200

Despite of the encouraging results shown in Fig.7 and the simplicity of the method, that is based on a basic principle of vibration systems, where the natural frequencies of a system change when its mass is varied, further investigation should be performed to evaluate the method. The influence of the spatial distribution of the phases and the influence of flow velocity should be extensively investigated. Tests performed in a wide range of flow conditions presenting different flow patterns, with different pipe geometries, are being performed by the authors.

8. CONCLUSIONS

A methodology for the measurement of two-phase flow rates based on the piping vibration response was presented and demonstrated. Results of a preliminary experimental investigation on the relationship between the pipe RMS acceleration and the mixture superficial velocity showed a strong correlation with a quadratic behavior. A method for the measurement of volume fraction based on the variation of pipe natural frequencies was also verified through experiments and numerical analyses. According to the proposed method, using the results obtained with accelerometers mounted to the pipe to obtain the relationship between the pipe RMS acceleration and the mixture superficial velocity and monitoring the variation of pipe natural frequencies due to changes in the volume fraction, one can measure the two-phase flow rates. Further investigations should be performed to evaluate the method under different circumstances. Nondimensional analysis and determination of the method uncertainty should also be performed. The measurement of pressure and temperature are also necessary to obtain complete information on the flow rates.

9. REFERENCES

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