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EXPERIMENTAL INVESTIGATION ON THE VIBRATION INDUCED BY SLUG FLOW IN HORIZONTAL PIPE

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ABSTRACT

Pipes used for transporting produced oil are often experienced two-phase flows. In particular, the presence of slug flow pattern will cause generation of transient pressure force and shear exerted on the interior wall of the pipe. This can cause vibration induced problems. This paper presents experimental results that enhance the understanding of the mechanism of fluid structure interaction FSI phenomena, and the nature of resulted vibration due to slug flows. Vibration measurements were taken under various slug flow rates. The effects of water superficial velocities on the vibration characteristics were investigated. The results showed that the pipe displacements of the vibration increased gradually with increased water superficial velocities, at a fixed air superficial velocity, while the predominant frequencies decreased progressively when the water superficial velocities was increased. In addition, the average maximum displacements increased by 64 % when the water superficial velocity increased from 0.65 m/s to 1.0 m/s. Meanwhile, a decrease of 9 % in the averages of the frequencies was noticed when the water superficial velocity increased from 0.65 m/s to 1.0 m/s. An investigation of the induced vibration behavior to change in air superficial velocities is recommended.

Keywords: slug flow, pipe vibration, fluid structure interaction.

INTRODUCTION

Transmission pipelines are the key arteries of the oil and gas business. They operate continuously on 24/7 bases to deliver the product. Industrial pipe systems are generally used in many arenas like hydropower power plants, transportation of the gas and oil, urban water supply and nuclear industry. Pipe systems facing the dynamic forces during coupling impact in between internal fluids and structure caused the pipe vibration and in certain cases rupture.

Internal two-phase flow through the production pipes is an example of the FSI, in which; the fluid pressures are transferred to the pipe wall and inversely the structural deformation represented by the displacement is transferred back to the fluid domain [1].

Overall, the most complicated phenomenon among all the internal two-phase flows in a pipeline is the slug flow. The major reason being it's associated local fluctuations of phase, i.e. intrinsically unstable. Apart from phase, there are other parameters such as: pressure, density, velocity, momentum flux as well as other hydrodynamic parameters. With such fluctuations, resonance could be generated as a result of the closeness between piping natural frequency, and the excitation force frequency [2]. As a result of such observation, performance of a designed system could be greatly hampered or in most cases destroy the system structure.

To design safe and reliable piping systems free from excessive vibrations, piping designer needs to know the frequencies of excitation forces in the piping and must be able to calculate the natural frequencies of the pipeline system [3].

Operating such pipelines at comparatively low flow rates and pressure could lead to the occurrence of long slugs. With the advent of such long slugs, serious operational problems could be encountered as a result of strong fluctuations in pressure or the flow supply [4].

Vibration in a piping system is a complex phenomenon not well understood by many pipework designers. Currently, there are no standards and just a few guidelines to assist in determining which systems might be at risk [5].

However, there are limited studies on the vibration characteristics which are induced by unsteady two-phase flow. Yih and Griffith [6] measured the force caused by two-phase flows impacting on a "turning tee." They found that low-frequency oscillation of the momentum fluxes can be important and is closely associated with the flow velocity. The authors [7, 8], presented detailed works on unstable forces produced by the two-phase flow. Furthermore, Riverin and Pettigrew [7] carried out an experimental investigation in small piping system comprising two elbows and straight sections configured in the form of a U-shaped pipe and subjected to air-water internal two-phase flow. The outcomes reveal that the major cause of pipe vibration was the resonance phenomenon between the periodic momentum flux fluctuations of air-water flow and the first modes of vibration of the piping system. Thus, there were proportional increases in the predominant frequency of excitation force with an increase in the mixture velocity. Gama et al. [9] presented an experimental investigation of the relationship between the air-water two-phase flow rates and piping vibration. Measurements of vibration were performed in two bends of pipe sections; the L-pipe and the U-pipe, for a given void fraction of air, the results showed that the vibration acceleration increased by the increase the mixture superficial velocity. Hemeda and Khalil [10] designed a small-scale experimental loop for testing the structural behavior of a horizontal cantilever flexible pipe conveying air and water two-phase flow.

They observed that the water slugs had an effect on the oscillating behavior of cantilever hose. Change in water superficial velocity affected on oscillation frequency of the hoses.

The information provided pertaining to the vibration characteristics induced by slug flows was insufficient. Where, the researchers discussed the induced vibration due to changes on the mixture superficial velocity, while the effect of superficial velocities of individual fluids has not been reported.

In practice, slug flow induced vibration has been identified as the reason for pipe fail in one of PETRONAS offshore platforms. And this case has been the driver for conducting this research work.

This project is trying to improve its comprehension of vibrations of horizontal pipes in the low-frequency range and to propose an approach method of analysis for the majority of the piping systems. An experimental study was undertaken to investigate the fluid structure interaction by measuring the induced vibration of pipe segment in the flow loop. Air/water has been injected into the flow loop at various flow rates. The influence of water superficial velocities on the pipeline vibration is analyzed, and the amplitudes and frequencies of the pipeline are computed.

EXPERIMENT SETUP

For the purpose of study the effect of induced vibration by slug flow in the horizontal pipe, the experimental test facility was build-up in the fluid laboratories of the Mechanical Engineering Department, Universiti Teknologi PETRONAS. The experimental facility consists of a horizontal measuring test section, air and water delivery systems, the two-phase mixer and instrumentations of the facility were modified in this study.

A schematic diagram of the air-water flow loop system used in this study is shown in Figure-1. The experiments were performed at room temperature (approximately 25 ^{o}C) and a pressure of 1 bar.

The flow testing pipe is a horizontal 8.0 m Perspex pipe of 74.0 mm diameter. It has been constructed by flange connected four sections, each of 2.0 m length that could be easily dismantled and re-installed. The flanges were mounted on fixed rigid steel frames in order to ensure fixed support and safe operating conditions. The test section, where the vibration measurements have been monitored, is a 2.0 m long starting from a distance of 6.0 m from the inlet. Figure-2 shows the test pipe with corresponding dimension.

The water phase flows in a circulation loop, while the air phase was released into the environment downstream of the horizontal test section, whereas two-phases were separated at the exit from the pipe.

Water was stored in two cylindrical PVC tanks. The first tank, with 100 gallon capacity, 1.0 m height and 1.2 m diameter was used to feed the closed loop through PVC pipe connected to the pump. The second tank, with 80 gallon capacity, was used to collect the return water from the test section. Both tanks are connected together through PVC pipe. The second tank was decided to be added after air bubbles were realized to flow through the pump and affect the readings of the ultrasonic flow measuring device. Hence, the purpose of the second tank is to prevent the air bubbles and debris transfer from the tank to the pump.

Water was fed to the test section through [EBARA 3M 50-125/2.2] pump, with 8 to 19 m pressure head corresponding to 60 and 24 m^3/h capacity. Calibrated ultrasonic flow meter with accuracy of ± 0.5% was utilized to measure the water flow rate. Sinusoidal valve was used to open/close the water supply.

Compressed air is used as the gas phase, supplied from a central compressor (Ingersoll Rand) type MM07931 DRBJ ADL, which deliver maximum air discharge of 42.5 m^3/min at pressure up to 0.85 MPa. The air mass flow rate is measured and controlled before entering into the two phase mixer using calibrated Omega FMA-2600A mass flow controller, which measured air flow within the range from 0-2.0 m^3/min and accuracy of ±0.05%, and then introduced into the mixer by a hose of 20 mm inner diameter.

Air and water were mixed at the air-water mixer section. This mixer was designed and fabricated for the generation of slug flow. As shown in Figure-3, water from the pump flowed to the mixture section vertically from the bottom to up. The air is charged into the mixer from a compressed air source through 0.02 m diameter flexible hose parallel to the main flow into the mixer.

The mixer section was designed with a plate in the middle to separate the air and water, and to avoid any perturbation that may occur in the inlet of the horizontal pipe, and to specify the stratification level at the pipe inlet. The mixer is made of PCV with T-section shape has two inlets one outlet. All openings are 74.0 mm diameters. The mixer is connected to the pipe by flanges.

From the mixer section, the air and water mixture flows along the horizontal pipe before reaching the test section where the accelerometer sensor was located. The accelerometer with sensitivity 100 mV/g mounted by a screw on the outside wall of the test section, at 7 m from the inlet to give the slug flow the enough length to grow and develop.

The electric signals were then converted to a digital signal through the NI USB-9234 with 24-bit resolution and maximum sampling rate 51.2 kHz and send to the computer as digital readings.

The Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) software developed by National Instruments was used for instrumentation control.

For each inlet slug flow rate, the slug flow visualization was obtained by using the high speed camera Phantom 9.1, with a recording rate of 1000 frames per second. The camera field of view is 960 (width) x 480 (height) pixels resolution. The output video signals were stored directly in the Random-access memory (RAM) of a personal computer and then conveyed to a hard disk for permanent storage.

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The adopted method for this experiment was to select a fixed air superficial velocity and incrementally increased the water superficial velocities up to the value in which the flow regime change from slug flow to another flow regime, then increasing the air superficial velocities and repeat the previous steps. The air and water superficial velocities used were selected from the Baker chart [11] to ensure that the resulted flow regime is slug flow only. In this study, the range of water superficial velocities was from 0.698 m/s to 1.0 m/s, whereas the air superficial velocities were between 2.094 m/s to 2.792 m/s.

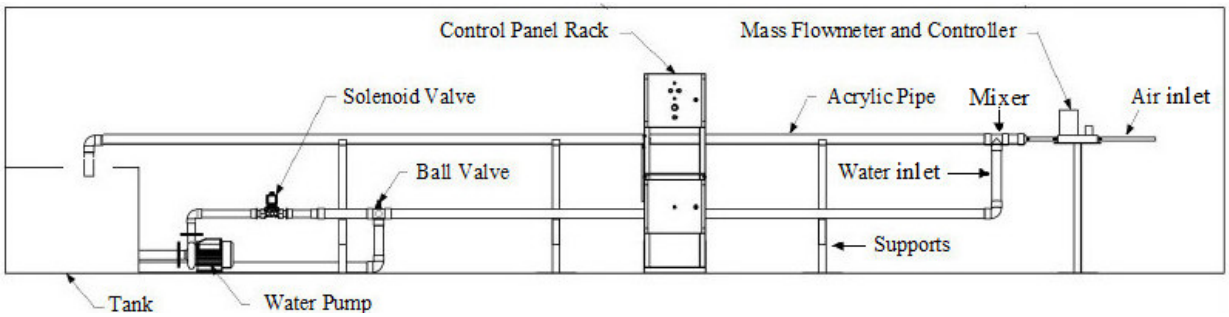

Figure-1. Schematic diagram of the experiment test facility.

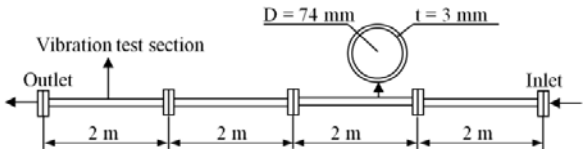

Figure-2. Dimensions of pipe test section.

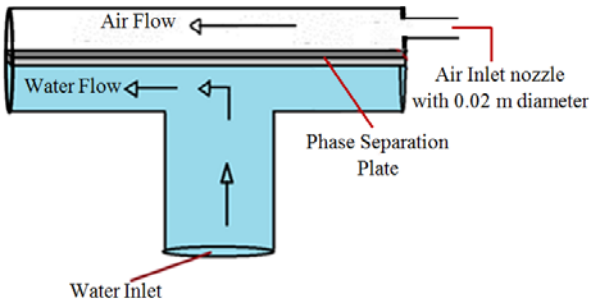

Figure-3. Air-water mixer section.

MEASUREMENT TECHNIQUES

Vibration measurements

In the present study, an online computerized interface system was used for the Vibration Data Acquisition and Analysis (VDAA). The vibration measurement was performed through sophisticated designed and fabricated VDAA including hardware and software parts. The system senses the physical phenomena, i.e. the vibration in the pipe by the accelerometer, transfers the signal to the Vibration Signal Analysis Software (VSAS) which utilized NI LabVIEW tools to manipulate the digital signals received from the NI USB-9234 and predicts the required variables in terms of displacement and frequency.

The vibration was measured during one hundred seconds using a rate of 2048 samples per second. The data was continuously taken every 0.0004 seconds over 100 seconds for each slug flow rate. The period of data acquisition should be sufficiently large to present a vibration data caused by the slug flow condition. Thus the 100 seconds data acquisition time was chosen based on the slug flow instability.

The Flow chart of the VSAS was shown in Figure-4. While, the items and the sequence of the VDAA system were illustrated in Figure-5.

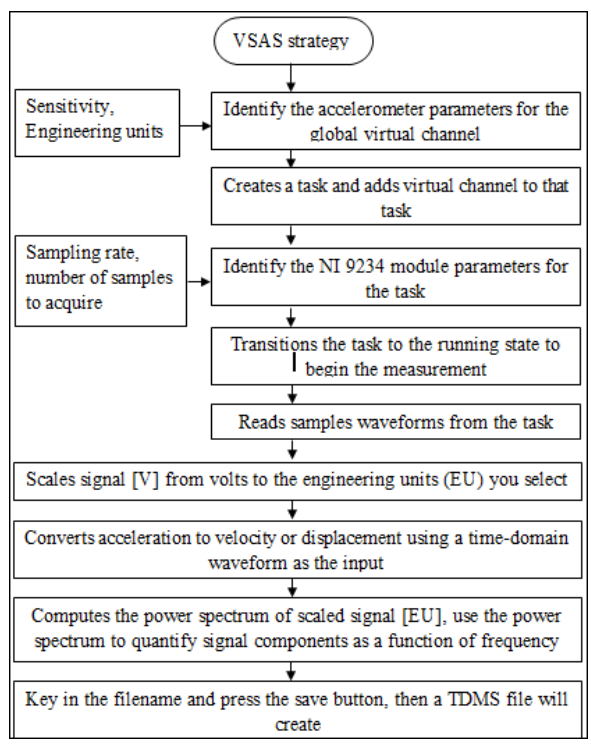

Figure-4. Vibration signal analysis software (VSAS) strategy.

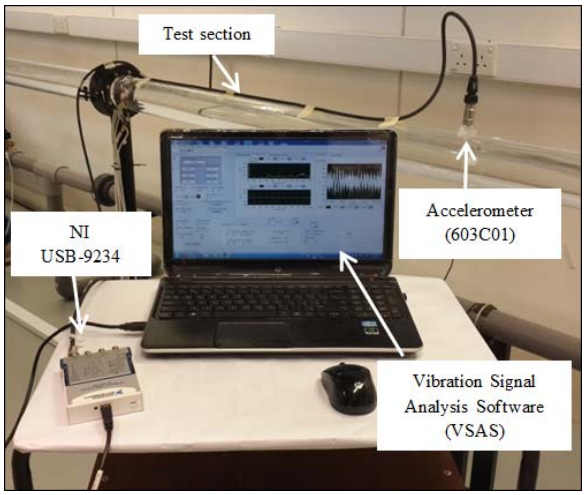

Figure-5. The photo of the arrangement for VDAA system.

RESULT AND DISCUSSION

When analyzing the vibrations in structure, two components are to be counted, namely: amplitude and frequency. Amplitude is the size of the vibration signal. Frequency is the number of times an event occurs in a given time.

The vibration results were measured by the developed VDAA system. Figure-6 shows in-plane the vibration displacements measured in the y direction at the top point in the mid-span of the test section of the pipe for different slug mixture superficial velocities U_M.

The U_M, resulted from the sum of the air superficial velocity, U_{SG}, and the water superficial velocity, U_{SW}. So, U_M always has a value greater than the air and water superficial velocities [12].

It was observed that the pipe vibration has a random behavior with periodic components. In addition, the increasing mixture of superficial velocities caused an increase of pipe displacements. Also, it is important to note that the peaks of displacement occurred once the slug passed through the measurement point on the test section of the pipe.

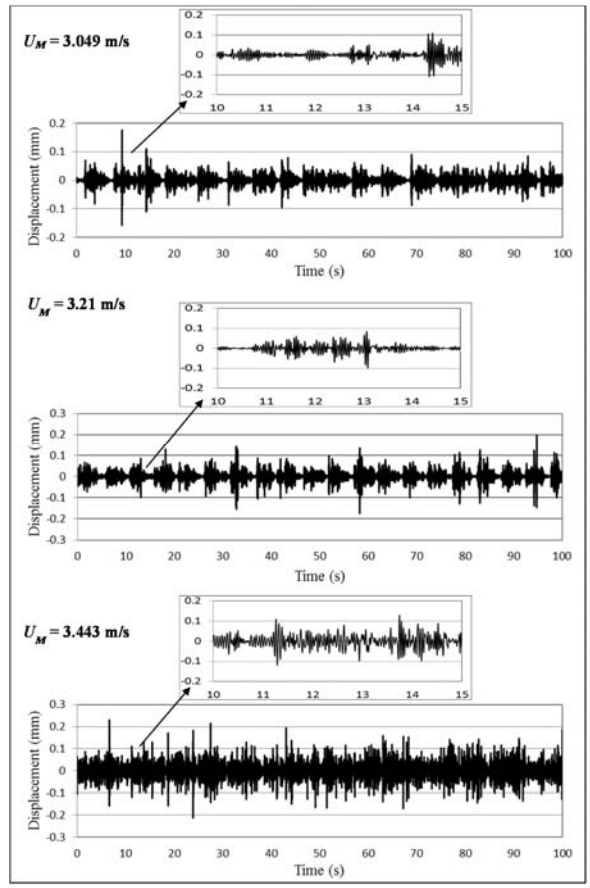

Figure-6. Displacements measured in the y direction for different mixture superficial velocities.

The typical time traces of displacement measurements were recorded, analyzed, and displayed as tables and plots. After that, the Power Spectral Density (PSD) was calculated from the displacement data recorded during each test performed according to the slug flow rates.

Figure-7 illustrates an example to find the pipe frequencies from the time domain using PSD of the displacement due to the passage of the slug through the test pipe.

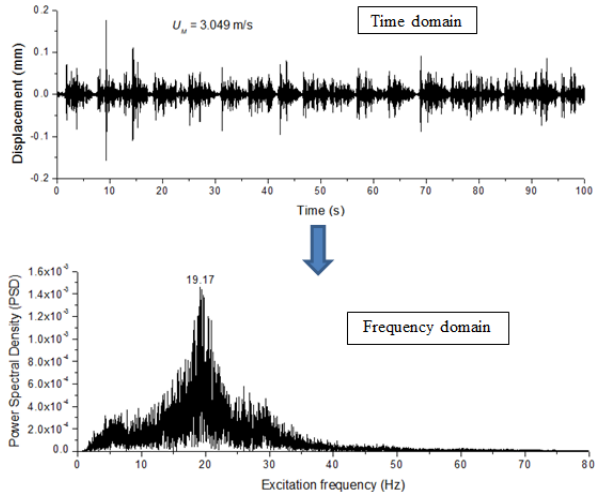

Figure-7. Example of in-plane frequency response.

Effect of Water Superficial Velocities on Vibration Response

In slug flow, when a water slug passes through the test section, dynamic forces will be imparted to it. Figure-8 indicates the measured pipe displacements in y direction, where, for a given air superficial velocity U_{SG}, it could be noted that the displacement increased when water superficial velocity U_{SW} increases within the range of 0.651, 0.698, 0.767, 0.86, 0.93 and 1.0 m/s. Moreover, the average of the maximum displacements was increased by 64 % when the water superficial velocities increased from the minimum of 0.65 m/s to a maximum of 1.0 m/s.

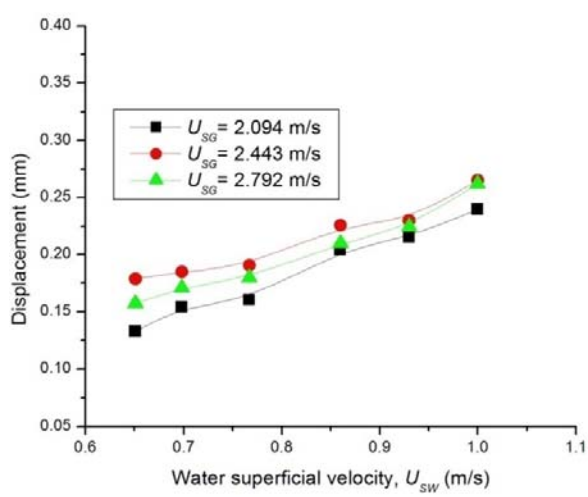

Figure-8. Effect of water superficial velocities on the vibration displacements.

On the other hand, with respect to constant air superficial velocity the predominant frequencies decrease gradually with increased water superficial velocities as shown in Figure-9. If the water superficial velocities increased at a constant air superficial velocity, the ratio of the water to the air through the slug unit will be increased. Therefore, the effect of the water mass which was added to the mass of the system should be inversely proportional to the frequencies. It was found that the average of the frequencies decreases by 9 % when the water superficial velocities increased from 0.65 m/s to 1.0 m/s.

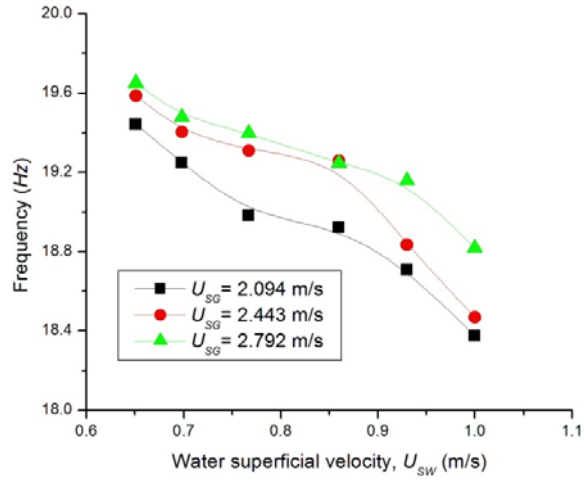

Figure-9. Effect of water superficial velocities on the vibration frequencies.

CONCLUSIONS

The experimental study of the effect of slug flow on vibration characteristics in horizontal circular transparent pipes was accomplished. The experiments were performed with air and water as the working fluids. It was observed that:

The vibration response of the pipe appears highly dependent on water superficial velocities.

For a given air superficial velocity, the vibration displacement increases when water superficial velocity increases. On the other hand, the average of maximum displacements increased by 64% when the water superficial velocity increased from 0.65 m/s to 1.0 m/s.

The vibration frequencies generally decreased with increasing water superficial velocities. Where, the average of the maximum frequencies decreases by 9% when the water superficial velocity increased from 0.65 m/s to 1.0 m/s.

The designer should bear in mind the limitation of the above results.

Further investigation into additional experimental results of the vibration characteristics at various air and water superficial velocities, is recommended.

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REFERENCES

[1] R.-j. QIAN, S.-l. DONG and X.-f. YUAN, "Advances in research on fluid-structure interaction theory [J]," Spatial Structures, vol. 1, p. 000, 2008.

[2] Y. Liu, S. Miwa, T. Hibiki, M. Ishii, H. Morita, Y. Kondoh, et al., "Experimental study of internal two-phase flow induced fluctuating force on a 90° elbow," Chemical Engineering Science, vol. 76, pp. 173-187, 2012.

[3] Z. I. Al-Hashimy, H. H. Al-Kayiem, F. Hasan, and A. Mohmmedd, "Effect of Various Fluid Densities on Vibration Characteristics in Variable Cross-section Pipes," Journal of Applied Sciences, vol. 14, p. 2054, 2014.

[4] U. Kadri, R. Henkes, R. Mudde, and R. Oliemans, "Effect of gas pulsation on long slugs in horizontal gas–liquid pipe flow," International journal of multiphase flow, vol. 37, pp. 1120-1128, 2011.

[5] A. Tijsseling and W. Dienstverlening, "Fluid-structure interaction in liquid-filled pipe systems: sources, solutions and unsolved problems," Report IWDE, pp. 02-05, 2002.

[6] T. Yih and P. Griffith, "Unsteady Momentum Fluxes in Two-Phase Flow and the Vibration of Nuclear System Components," in Proceedings of the International Conference on Flow-Induced Vibrations in Reactor System Components, Argonne IL Report ANL-7685, 1970, pp. 91–111.

[7] J.-L. Riverin and M. Pettigrew, "Vibration excitation forces due to two-phase flow in piping elements," Journal of Pressure Vessel Technology, vol. 129, pp. 7-13, 2007.

[8] J. Riverin, E. De Langre, and M. Pettigrew, "Fluctuating forces caused by internal two-phase flow on bends and tees," Journal of sound and vibration, vol. 298, pp. 1088-1098, 2006.

[9] A. L. Gama, L. R. dos Santos Ferreira, and P. H. A. Walter Filho, "Experimental Study on the Measurement of Two-Phase Flow Rate Using Pipe Vibration," in Proceedings of 20th International Congress of Mechanical Engineering, COBEM, 2009, pp. 15-20.

[10] M. Hemeda and A. K. H. Khalil, "Structure-Slug Flow Coupling: Small Scale Experiments with Submerged Flexible Pipes," M. Sc., Norwegian University of Science and Technology, 2015.

[11] O. Baker, "Simultaneous flow of oil and gas," Oil Gas J, pp. 185-195, 1954.

[12] Z. I. AL-HASHIMY, H. H. AL-KAYIEM, R. W. TIME, and Z. K. KADHIM, "Numerical Characterisation Of Slug Flow In Horizontal Air/water Pipe Flow," International Journal of Computational Methods and Experimental Measurements, vol. 4, pp. 114-130, 2016.