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Simultaneous Measurement of Liquid Velocity and Interface Profiles of Horizontal Duct Wavy Flow by Ultrasonic Velocity Profile Meter

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ABSTRACT

A simultaneous measurement of the liquid velocity and interface profiles was performed for stratified-smooth and wavy flows in a horizontal duct using a Ultrasonic Velocity Profile Monitor (UVP) Model X-1. Both parameters were successfully measured for the wavy flows with periodical interfacial waves when the influences of multiple reflections of ultrasonic pulses between the gas-liquid interface and the channel bottom was avoided well. Good comparison with the liquid level and velocity profiles measured by other methods was obtained for the smooth-stratified flow. The wavy flow data agreed well with the theoretical prediction of the liquid velocity profile around solitary waves.

1. Introduction

Liquid-phase velocity profile below interfacial waves in horizontally-stratified gas-liquid two-phase flows affects the interfacial exchanges of mass, momentum and heat, and the growth of the interfacial waves. For the cases of practical importance, such as stratified-wavy two-phase flows, it is generally difficult to predict theoretically or measure experimentally the liquid-phase velocity profile that is coupled with the wavy interface profile. The theoretical velocity profile with the wavy interface profile is available only for limited cases like infinitesimal and solitary waves.

The UVP is one of the promising instruments for dynamic measurement of the velocity profile of the liquid flow. However, the use of the UVP in wavy flows has encountered difficulties by the reflection of the ultrasonic pulses at the gas-liquid interface. In JAERI, the UVP measurement not only of the velocity profile, but also of the interfacial wave profile, was successfully performed in the horizontal wavy flow experiments. This paper describes the application method of the UVP on the wavy flows and the obtained results.

2. Experiment

2.1 Test Facility

Figure 1 shows a schematic view of the test facility. The horizontally-leveled test section (a 0.1 m-wide, 0.7 m-high, 28.3 m-long duct) is made primarily of transparent acrylic resin to visually observe the flow. Demineralized-water in a 10-m^3 outlet tank (not shown) is recirculated by pumps to the bottom of inlet tank. Water flow rate is measured by orifice meters. A constant water flow rate of 4.17 x 10^{-3} m^3/s was used for the present experiment. The liquid level in the outlet tank was kept lower than the bottom of the test section to attain free out-flow due to the gravity. The liquid level at the test section exit was thus close to the critical level. A wave generator in the inlet tank was used to generate periodical interfacial waves to compare the data with the theoretical prediction. Stratified-smooth flow with no interfacial waves appeared when the wave generator was stopped. The experiments were performed under atmospheric-pressure, room-temperature conditions.

2.2 *Instrumentation*

Both the velocity profile and liquid level were measured by the UVP. The UVP sensor was inserted from the bottom of the acryl-made test section facing towards upstream with an angle of 10° from vertical. The top surface of the UVP sensor was placed to be flush with the bottom of liquid stream. The liquid level was measured also by an electrical resistance method, simultaneously with the UVP, using a pair of parallel-wire electrodes (0.09 mm outer diameter, 60 mm apart) made of platinum-coated tungsten. The electrodes were mounted vertically on a plane perpendicular to the flow axis, in which the top of the UPV sensor was located. The liquid level and velocity profile at the same location were measured simultaneously.

Polystyrene beads with a density of 1.01 and diameters of 0.1 to 0.5 mm were used as reflectors of ultrasonic pulses. The polystyrene beads were injected with water through a nozzle at 1.0 m upstream of the UVP sensor as shown in **Fig. 1**.

The gas-liquid interface totally reflects ultrasonic pulses back towards the test section bottom. Multiple reflections between the interface and the test section bottom as shown in **Fig. 1** was observed to occur inherently. Thin (~2 mm) butyl rubber sheet[1] with many tiny dips made by needle tips was placed on the bottom inner wall to absorb the ultrasonic pulses. However, the ultrasonic pulse after one time reflection at the test section bottom was still strong enough to cause an overlap of the echo signal onto that from the next pulse. The intensity of the echo from the remaining pulse after the second reflection was negligiblly small for signal processing. Therefore, the "maximum measurement depth" was chosen to become more than twice as large as the liquid level to give a long time interval between two pulses. Bit manipulation of the measured data was necessary to expand the velocity range.

Both the liquid level and velocity profile were measured also by using a flow visualization technique composed of the laser-sheet lighting of polystyrene beads as reflectors for the UVP. Two-dimensional (2D) NTSC video pictures of the flow with beads were taken simultaneously with the above level and velocity profile measurements. The velocity profile for smooth-stratified flow was obtained by the "Current" particle tracking velocimetry (PTV) (KANOMAX Inc.) that employs a four-points particle tracking method.

3. Measured Results and Discussion

Figure 2 compares the UVP velocity profiles with the liquid level data for a smooth-stratified flow. The UVP velocity profile data was found to have a dip at the liquid level of 120 mm. Echoes from a ultrasonic pulse usually propagate isotropically in water. At the gas-liquid interface, however, both the pulse and echoes would reflect together towards a certain direction, causing such a dip in the velocity profile. The direction of the reflected echo and ultrasonic pulse depends on the orientation of the interface. The UVP velocity data appearing above the liquid level in **Fig. 2** are based on echoes from the ultrasonic pulse after one reflection at the gas-liquid interface. These data may be valuable when the path of the reflected pulse can be identified.

Agreement between the UVP data and liquid level data was good when the sound velocity of 1442.5 m/s was used instead of 1479.0 m/s for water at temperature of 17 °C. A large fluctuation appeared in the transient velocity profile data as typically shown in **Fig. 2**, probably because of a turbulent structure in the flow at the Re number of 3.2 x10^4.

Figure 3 compares the average UVP data for the smooth-stratified flow with the average velocity profile obtained by the "Current" PTV. The horizontal bars in **Fig. 3** are the standard deviation σ of the UVP data. A large fluctuation in the UVP data due probably to the turbulence in the flow resulted in a large value of σ. The average PTV data was obtained from 1) piling up several 2D data each of which contains velocity vectors for tracked particles, 2) interpolating these randomly distributing velocity data onto the 2D velocity matrix (31 x 31) points using continuity equation, and 3) sum-averaging the same-elevation data of the matrix to obtain vertical velocity profile shown in **Fig. 3**.

The UVP data agreed fairly well with the PTV data except those near the channel bottom where the PTV constructed the 2D velocity distribution using small number of tracked particles. The uncertainty in the PTV increases as the number of particles effective for construction of the velocity distribution decreases.

Figure 4 indicates a typical result of the wavy flow experiments. Theoretically-obtained velocity profiles of the solitary wave[2] propagating with a certain wave celerity[3] are compared with the UVP data. The theoretical value is summed with the average velocity distribution obtained from the previous smooth-stratified flow experiment. The agreement of the data with the theoretical prediction is good, while the measured velocity was always larger than the predicted velocity in the wave above the equilibrium liquid level. The interfacial waves generated by the wave generator in this experiment may be steeper than the theoretical solitary wave. In this comparison, fluctuation in the measured velocity profile appeared again, as in the smooth-stratified flow. The dip in the velocity profile that indicates the location of the liquid level was not so clear in this case as shown in **Fig. 4**, probably because the interface was more ragged than that for the smooth-stratified flow.

In the wavy-flow experiments, it was difficult to use short measurement range that has large velocity range, because of multiple reflection of the ultrasonic pulses as noted before. The wider UVP velocity range is preferable to study characteristics of the large-size waves, since the liquid-phase velocity profile of the wavy flow depends on the wave amplitude, length and liquid depth.

4. Summary

Both the water velocity and gas-liquid interface profiles of smooth-stratified and wavy flows were successfully measured using the UVP Model X-1. Special cares were taken to reduce the significant influence of reflection of the ultrasonic pulses at the gas-liquid interface. These measured UVP parameters agreed well with the velocity profile obtained by the PTV based on the flow visualization and the liquid level measurement. Wider range of the measuring velocity in shorter data processing time is desirable for an advanced application of the UVP onto large-amplitude wavy flows.

5. References

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[3] R.L. Wiegel, Oceanographical Engineering, Prentice-Hall, 65-76 (1964).

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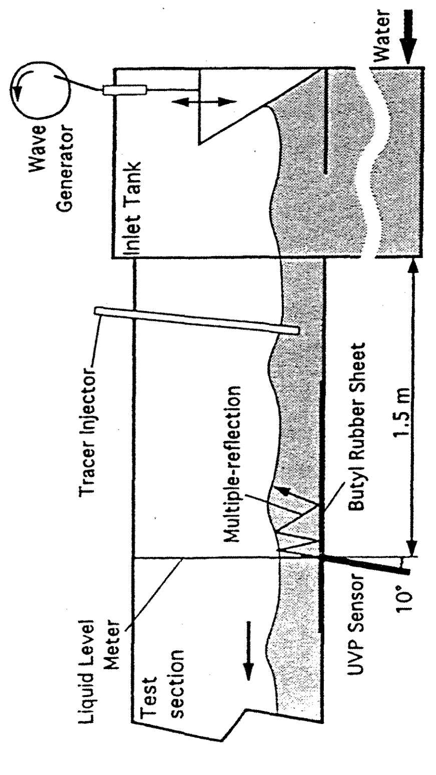

Fig. 1 Schematic of Experimental Setup

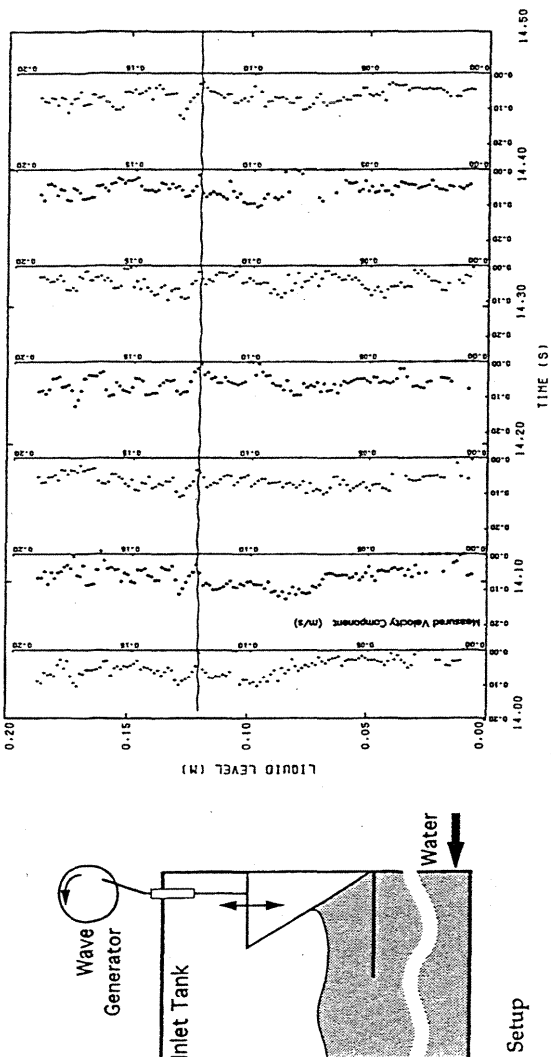

Fig. 2 Comparison of Typical Transient Velocity Profile Data with Liquid Level Data for Smooth-stratified Flow

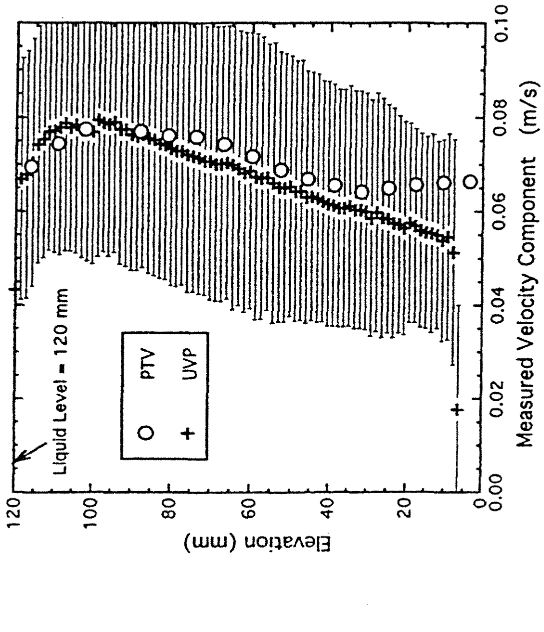

Fig. 3 Comparison of Average Velocity Profiles obtained by UVP and PTV

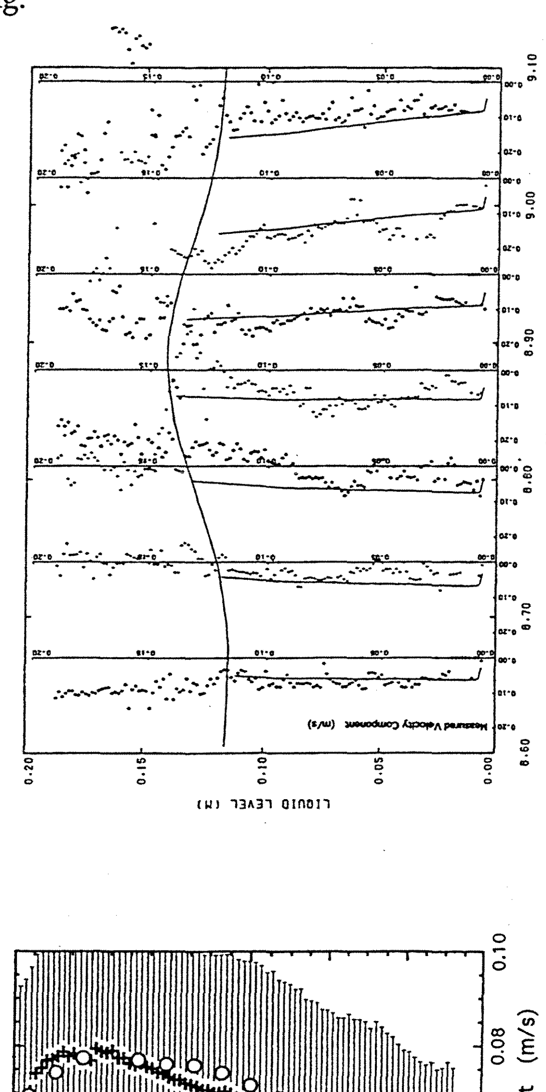

Fig. 4 Comparison of Typical Transient Velocity Profile Data with Liquid Level Data and Theoretical Velocity Profiles for Wavy Flow