Development of a Budget Multiwave UVP System for Two-phase Flow Measurement and Some Applications

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The ultrasonic velocity profile (UVP) method is a powerful tool for the measurement of spatio-temporal velocity distribution of fluid flows. The multiwave UVP method is capable of measuring simultaneously and separately instantaneous velocity profiles of the liquid- and bubble-phase in bubbly flow. Reducing the cost of the UVP systems is always of significance and interest, especially for developing countries. This paper presents the development of a budget multiwave UVP method. Instead of using costly tone-burst pulser/receivers (P/Rs), inexpensive spike P/Rs are exploited. The P/Rs generate spike signal to excite ultrasonic sensors. The auto-correlation pulsed Doppler signal processing is used. The spike-excitation multiwave UVP method is first validated by the measurement of single-phase pipe flow. For two-phase flow, the method is validated by the measurement of air-water counter-current bubbly flow in a vertical pipe. The system is used in a new method to measure the bubble condensation rate in subcooled boiling. Measurements of other two-phase flow configurations with heat/mass transfer are undergoing. The cost of a custom-built spike-excitation multiwave UVP system is approximately about less than one third of that of a commercial UVP system. Consequently, the application of the UVP method can be more expanded.

Keywords: UVP, Two-phase flow, Spike excitation, Damping effect, Boiling two-phase flow

1. Introduction

In the study of fluid thermodynamics, the spatial-temporal velocity distribution of fluid flows is of great importance. For single-phase flow, instantaneous velocity profile is required to analyze the flow characteristics in, for example, turbulent flow, etc. In such cases, there is no analytical description of the flow parameters. For two-phase bubbly flow, the problem is more complicated since instantaneous velocity profiles of both phases are required. Therefore, the development of the methods to measure instantaneous velocity profiles of fluid flows without/with heat mass transfer is crucially important.

There are very few methods for the measurement of the velocity distribution of fluid flows. These methods include the PIV (Particle Image Velocimetry), PTV (Particle Tracking Velocimetry) and UVP methods. The PIV and PTV methods require optical access into the flow field. Moreover, PIV/PTV measurement of two-phase flow is highly complicated. On the other hand, the ultrasound techniques, for example, the UVP and multiwave UVP methods for single- and two-phase flow measurements, respectively, can also measure instantaneous velocity distributions along the sound path. Measurements do not require optical access into the flow field. Moreover, non-intrusive, non-contact measurement of existing flows can be possible. These characteristics make the methods powerful for the study of fluid dynamics. However, the commercial ultrasonic systems are high cost. As a result, the development of budget systems is of considerable interest.

In the UVP method, the active element of the ultrasonic sensor emits ultrasound when it is stimulated by an electrical excitation signal. Commercial systems typically use constant amplitude tone-burst (or sinusoidal) excitation signal. The hardware is therefore high cost. In contrast, spike signal is most widely used in the nondestructive testing (NDT) industry. The signal generated from spike pulsers has a wideband frequency spectrum. Previously, it was not used with the Doppler method. The spike length is usually shorter than that of the tone-burst. Hence, the spike signal enables high spatial-resolution measurements. In addition, the spike-pulser circuit has simple design and is less expensive. Hence, the application of the spike excitation to the Doppler UVP measurement can significantly reduce the hardware cost. Besides, it can exploit the advantages of the Doppler signal processing.

This paper presents the use of the spike excitation with the Doppler signal processing for UVP measurement. The damping of the spike excitation has been found to be the key. Slowly damped spike excitation can enable velocity measurement by using the Doppler signal processing and the UVP sensor of the Doppler method. A multiwave UVP system has been developed. A satisfactory accuracy of the measured data of single- and two-phase flows has been confirmed. Some measurement applications carried out in the Laboratory for Industrial and Environmental Fluid Dynamics, IMECH, VAST are presented.

2. Development of the spike-excitation multiwave UVP system

2.1 Spike-excitation for the UVP method (single-phase flow measurement)

In conventional UVP systems, tone-burst signal of constant amplitude, specific number of wave cycles, and center frequency f_0 (Fig.1(a)) is used. f_0 is set the same as the sensor resonant frequency. Under such excitation, the emitted ultrasound typically has the shape shown in Fig.1(b). The number of wave cycles is an adjustable parameter, in advanced UVP systems. The design and implementation of such P/R hardware is complicated and expensive.

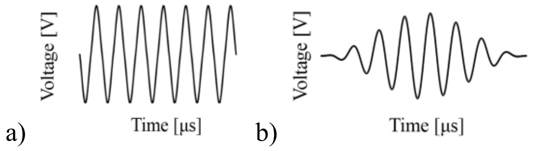


Figure 1: (a) Sinusoidal excitation signal, (b) emitted pulse.

Spike excitation is widely used in the ultrasonic testing and imaging. Under spike excitation, the sensor emits short pulses that help to improve the spatial resolution. Excitation spike (Fig.2) is characterized by a short length and a wide frequency band. A spike can be defined by a time varying voltage $V_i(t)$ as shown in Eq.1.

$$V_i(t) = \begin{cases} 0 & t \le 0 \\ -V_\infty\left[1-\exp(-\alpha_1 t)\right] & 0 \le t \le t_0 \\ -V_0 \exp\left[-\alpha_2 (t-t_0)\right] & t \ge t_0 \end{cases} \tag{1}$$

where $V_\infty = V_0 / \left(1-e^{-\alpha_1 t_0}\right)$. The parameters t_0, α_1, α_2 and V_0 specify the spike amplitude, rise and fall characteristics. Intuitively, the signal's fall characteristic which is determined by the signal damping has decisive effect on its power spectrum. Slowly damped signal lasts longer than highly damped one.

The excitation method affects the number of wave cycles N and the center frequency f_0 of the emitted pulse. In the Doppler method, N and f_0 are required to calculate the spatial uncertainty and the flow velocity, respectively. When the tone-burst is used, the length and frequency of the emitted ultrasonic pulses depend on the excitation signal characteristics, the sensor damping, etc. The emitted-pulse's length can be controlled by using the excitation-signal's length N. The tone-burst excitation optimizes the generation of high signal to noise ratio (SNR) ultrasound. When the spike excitation is used, the frequency of the emitted pulses is primarily decided by: (a) the forced oscillations imposed by the spike, (b) the ringing of the sensor's active element (i.e. the resonant frequency f_0). The emitted ultrasound has a wide bandwidth, low SNR.

Experimental investigations have been carried out and the following conclusions have been obtained. When the excitation spike is highly damped (i.e. at minimum damping parameter R_d or Min R_d shown in Fig.3), the emitted ultrasound has poor SNR and cannot be used with the Doppler signal processing. When it is slowly damped (i.e. at maximum R_d or Max R_d in Fig.3), the emitted pulse is well defined and has good SNR. It can be used with the Doppler signal processing. Experimental measurements have confirmed the high accuracy of the measured velocity profiles [1]

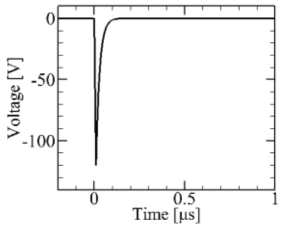


Figure 2: Theoretical spike with t_0 = 0.01 µs, α_1 = 0.2, α_2 = 50, V_0 = 120 V.

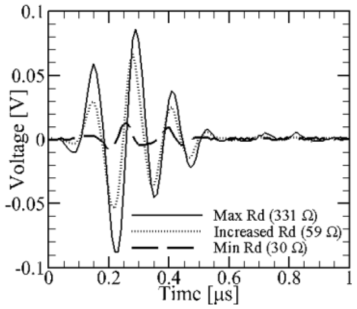


Figure 3: Emitted ultrasonic pulses corresponding to varied damping parameter R_d of the spike P/R.

2.2 Spike-excitation multiwave UVP method

The spike excitation and the Doppler signal processing are then applied to the multiwave UVP method. The program flowchart is shown in Fig.4.

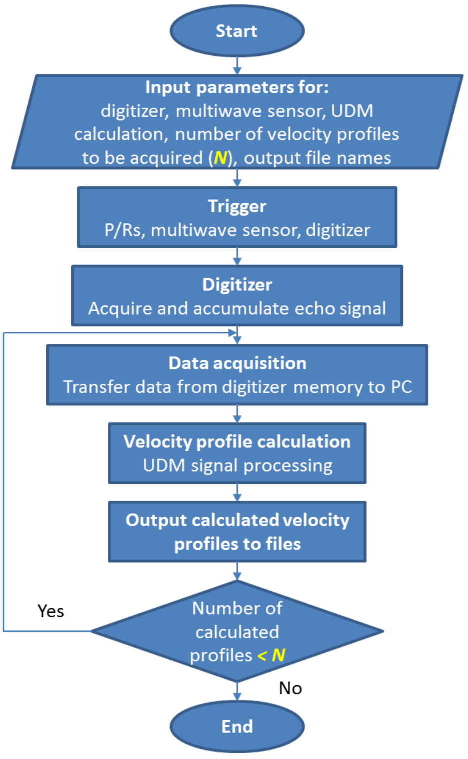


Figure 4: The flowchart of the multiwave UVP method.

2.3 Auto-correlation Doppler signal processing

The received echo signal is digitized by using a highspeed digitizer. The digitized signal is demodulated into in-phase and quadrature-phase components. The auto-correlation signal processing which is based on the Wiener-Khinchine theorem is exploited for the detection of the Doppler shift frequency. This technique might be most suitable for the processing of wide bandwidth signal. Our pilot investigations showed that high-accuracy velocity measurement by using spike excitation is enabled by the combination of spike signal and the auto-correlation signal processing.

2.4 Spike-excitation multiwave UVP system

The system is shown in Fig.5 [2]. It consists of:

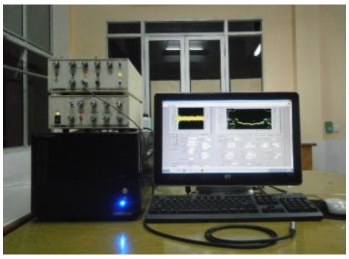


Figure 5: The multiwave UVP system in IMECH, VAST.

a) Multiwave sensor (Japan Probe Co. Ltd.): 2 and 8 MHz frequencies;
b) Two spike P/Rs (JSR DPR300 and JSR DPR35+, JSR Ultrasonics Co., Ltd.);
c) Two-channel digitizer (NI PCI-5112, National Instrument Co. Ltd.): resolution: 8 bits; max. sampling rate: 100 MHz; 16 MB memory;
d) PC for data acquisition and signal processing.

The software has been developed by using LabView (for signal acquisition), C++ (for Doppler signal processing).

3. Comparison with commercial UVP

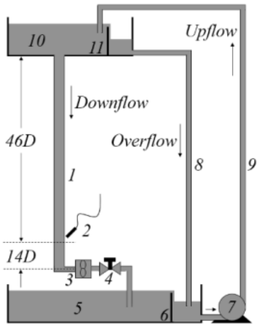
As mentioned previously, the most important aspect of the custom developed system is the lower cost. In addition, one more advantage of the system is the ability to classify exactly between zero velocity (no fluid flow) and the no velocity value (failure calculation of velocity) at a point along a measured profile. In a commercial UVP, usually, no velocity value is assigned to be zero.

4. Applications

4.1 Measurement of single-phase flow

A schematic drawing of the apparatus is shown in Fig.6. The 8 MHz element of the multiwave sensor is used. The sensor is fixed at 64D from the pipe inlet, 14D from the pipe end (D: pipe inner diameter). Nylon powder is used as the seeding particles. Reynolds number (Re) is 5500. A water box is used to couple the sensor to the test pipe.

The Doppler angle is 45°. Figure 7 shows the mean velocity profile *u*+ in the wall unit *y*+. Good agreement between the measured profile and the logarithmic law has been obtained. The error bars show the standard deviation from the mean value. By using the measured velocity profile, a comparison with the flowmeter data showed a small error which is less than 1%.



1: test pipe
2: multiwave sensor
3: turbine flow-meter
4: needle valve
5, 10: floor, upper tanks
6, 11: overflow weirs
8: overflow pipe
9: up-flow pipe

Figure 6: Experimental apparatus for the measurement of single-phase flow.

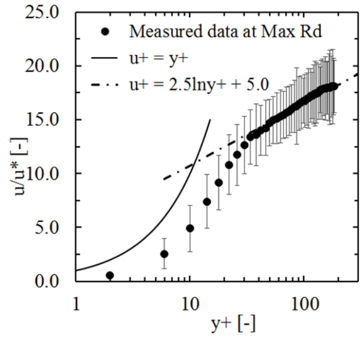


Figure 7: Comparison with the logarithmic law.

4.2 Measurement of air-water bubbly flow

Counter-current bubbly flow is generated in the test pipe (D = 50 mm) made of transparent acrylic (Fig.8). Water flows down; air bubbles rise upwards.

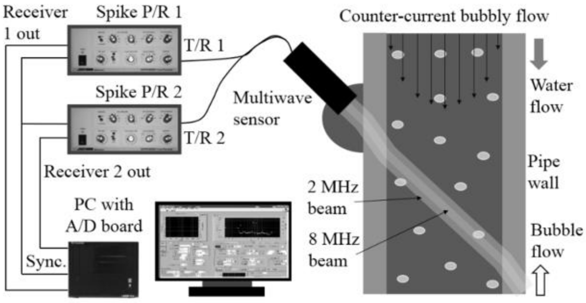


Figure 8: Spike excitation multiwave UVP system and the test section of the flow.

Liquid velocity profile is measured by the 8 MHz frequency. Bubble velocity profile is measured by the 2 MHz frequency. The velocity probability density functions (PDFs) at the pipe center are shown in Fig.9. The PDF of the 2 MHz data shows only one peak that occurs at the dominant bubble velocity. The 8 MHz data mainly contains liquid velocity but includes some bubble data. The PDF of the 8 MHz data has two peaks corresponding to the liquid and bubble velocities.

It would be worth mentioning that, with our custom-developed multiwave UVP system, the same pulse repetition frequency (PRF) is used for both frequencies.

Hence measurement of phase velocity profiles at the same time is secured by using the same number of pulse repetitions for velocity calculation. The same spatial resolution is absolutely assured by choosing the same number of digitized data points in the spatial domain for each measurement volume of both frequencies.

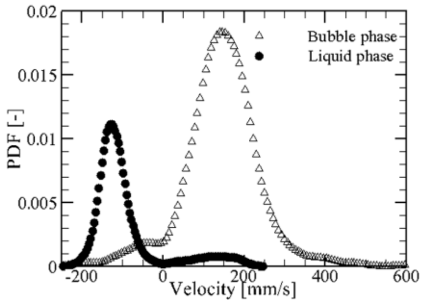


Figure 9: Velocity PDFs calculated from the measured data of the 2 MHz and 8 MHz frequencies at pipe center.

4.3 Measurement of subcooled boiling

The condensation rate of vapor bubbles (defined by v_c=-dR/dt where R is the spherical-equivalent bubble radius) can be calculated by using the measured data of two simultaneous UVP measurements. The two sensors TDX1 and TDX2 are arranged as shown in Fig.10. The top- and bottom-surface velocities of vapor bubbles are measured by TDX1 and TDX2, and denoted by V_{TDX1} and V_{TDX2}, respectively. The bubble condensation decreases the velocity of the top interface. Hence, the measured data by TDX1 can be expressed as:

$$V_{TDX1} = V_b\cos\theta - v_c \qquad (2)$$

where V_b is the bubble rising velocity. On the other hand, the condensation increases the velocity of the bottom interface of the bubble. Hence, the measured data by TDX2 can be written as:

$$V_{TDX2} = -(V_b\cos\theta + v_c) \qquad (3)$$

where the minus sign implies that the bubble movement in the sound path of the TDX2 is away from the sensor surface. From Eq.2 and 3, the condensation rate v_c can be calculated by eliminating the bubble velocity V_b [3]:

$$v_c = -(V_{TDX1} + V_{TDX2})/2. \qquad (4)$$

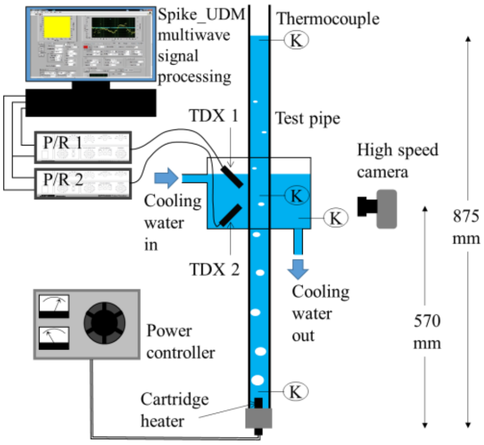


Figure 10: Experimental apparatus of subcooled boiling.

Based on the principle of condensation-rate measurement, experiments have been carried out for varied liquid subcooling temperature. In addition, flow visualization has also been carried out. The measured data are shown in Table 1. By using the measured v_c, the interfacial condensation Nusselt number Nu_c is calculated and compared with the published correlations. Fairly good agreement has been obtained as shown in Fig.11.

Table 1: Average condensation rate, bubble rising velocity and bubble diameter for varied degrees of liquid subcooling.

Liquid subcooling degree (°K)	4.6	4.4	4
Condensation rate v_c measured by using spike-excitation UVP (mm/s)	21.1	12.9	5.4
Bubble rising velocity measured by using spike-excitation UVP (mm/s)	303	246	179
Average spherical-equivalent bubble diameter measured by optical visualization (mm)	13	9.4	4.5

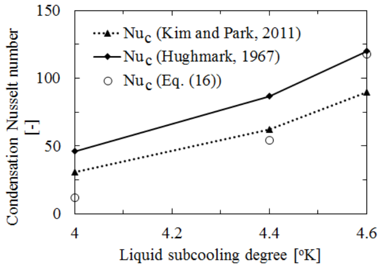


Figure 11: Comparison between the measured Nu_c with the results of other correlations.

5. Concluding remarks

Spike excitation and the pulsed Doppler signal processing have been successfully applied to the UVP method.

Based on the spike excitation technique, a multiwave UVP system for two-phase flow study has been developed. The cost of the system can be reduced significantly as compared with the commercial UVP.

Applications of the custom developed system to fluid dynamic research at the IMECH, VAST have been succesfully carried out.

References

[1] Nguyen TT, *et al.*: Ultrasonic Doppler velocity profile measurement of single- and two-phase flows using spike excitation, Exp. Techniques (2016), 1-14.

[2] Nguyen TT, *et al.*: Development of multiwave method using ultrasonic pulse Doppler method for measuring two-phase flow, J. Japan Soc. Exp. Mech. 13 (2013), 277-284.

[3] Nguyen TT, *et al.*: Measurement of the condensation rate of vapor bubbles rising upward in subcooled water by using two ultrasonic frequencies, Int. J. Heat Mass Transfer 99 (2016), 159-169.