VIETNAM ACADEMY OF SCIENCE AND TECHNOLOGY

Vietnam Journal of MECHANICS

Volume 35 Number 3

ISSN 0866-7136

VN INDEX 12.666

3

2013

35th Anniversary

Vietnam Journal of Mechanics, VAST, Vol. 35, No. 3 (2013), pp. 239 – 256

MEASUREMENTS OF SINGLE-PHASE AND TWO-PHASE FLOWS IN A VERTICAL PIPE USING ULTRASONIC PULSE DOPPLER METHOD AND ULTRASONIC TIME-DOMAIN CROSS-CORRELATION METHOD

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Abstract. Ultrasonic Velocity Profile (UVP) method for measurement of single-phase and two-phase flow in a vertical pipe has recently been developed in the Laboratory for Industrial and Environmental Fluid Dynamics, Institute of Mechanics, VAST. The signal processings of the UVP method include the ultrasonic pulse Doppler method (UDM) and the ultrasonic time-domain cross-correlation (UTDC) method. For two-phase flow, simultaneous measurements of both liquid and gas are enabled by using a multi-wave ultrasonic transducer (multi-wave TDX). The multi-wave TDX is able to emit and receive ultrasounds of two different center frequencies of 2 MHz and 8 MHz at the same time and position. 2 MHz frequency with beam diameter 10 mm is exploited for measurement of gas. 8 MHz one with beam diameter 3 mm is used for liquid. Measurements have been carried out for laminar and turbulent single-phase flows and bubbly counter-current two-phase flows in two flow loops using two vertical pipes of 26 mm inner diameter (I.D.) and 50 mm I.D. respectively. Based on the measured results, assessment of each method is clarified. Applicability of each method for different conditions of pipe flow has been tested. Suggestions for application of the two methods have been recommended.

Keywords: Velocity measurement, non-contact measurement, UVP, two-phase flow, pipe flow, bubbly flow, UDM, UTDC.

1. INTRODUCTION

In the study of fluid mechanics, both experimental measurement and numerical simulation are of great importance. Flow parameters and scalar transport variables (both averaged and instantaneous quantities) including velocity of fluid and particles, pressure, temperature, particle concentration etc. are required to clearly understand the flow behavior and transport phenomena. Velocity is one of the most important parameters to understand flow dynamics, turbulence structures and heat/mass transfer etc.

Advanced CFD (Computational Fluid Dynamics) codes can be used to simulate internal and/or external fluid flows in highly complicated geometries. However, reliable results of CFD simulation can only be obtained if the numerical models are well calibrated, validated and verified. This, for the most part, relies heavily on results of experimental measurements. Moreover, numerical models based on CFD codes require measured data for boundary conditions which is usually provided by only experimental measurements. In addition, to some extent, CFD codes may suffer from approximations and simplifications of the mathematical and/or physical problems and phenomena. For example, one must rely on many approximations for flows with discontinuity in the case of single-phase flows, and for flows with separation interfaces (e.g. liquid-gas) in the case of two-phase flows. Therefore, if one wants to know exactly and precisely how flows develop, only experimental measurement can be suitable.

For measurement of velocity of fluid flows, especially the ones in laboratory scale models, a range of measurement methods have been devised using, for example, flow marking, Pitot tube, hot-wire sensor, conductivity electrode, flow visualization etc. However, these measurement methods all have some difficulties in measuring velocity inside the flow field. They either disturb the flow by the insertion of measuring probes into the flow (i.e. intrusive effect) or need an optical window for flow measurement. In addition, very few methods can provide instantaneous velocity profiles of flows, especially flows in operation. Moreover, these methods usually work with single-phase flows only. Their application to two-phase flows is not straightforward. It is therefore highly desirable to have non-intrusive, non-contact measurement methods that can work for both single-phase and two-phase (and even three-phase) flows. Moreover, such measurement methods should have capability to provide instantaneous velocity profiles of the flow under investigation.

Therefore, the UVP measurement method exhibits many appropriate characteristics to fulfill the needs. This method has origin from medical applications of ultrasound for measurement of velocity of blood flow [1, 2]. In UVP method, the ultrasonic TDX emits a number of ultrasonic pulses into the flow field in a very short time. After the emission of each pulse, the TDX itself receives the echo back-scattered from ultrasonic scatterers in the flow until the next pulse is emitted. Echo data resulted from ultrasonic scatterers is analyzed to get instantaneous velocity profiles along the sound path. This is a fully non-intrusive, non-contact measurement method since ultrasound can penetrate many kinds of flow boundaries and fluids. The method can work with both opaque fluid and non-transparent boundaries of flow. Moreover, this method can provide online, instantaneous velocity profiles of experimental/industrial flows in systems under operation. Hence, UVP method is very strong for applications to flow measurements.

Application of UVP method to scientific and engineering problems dated back to its first application to the measurement of Poiseuille flow in a pipe and Taylor vortex flow in two concentric rotating cylinders by Takeda [3]. Since then, lots of applications and development of UVP method have been carried out. A large number of practical applications of UVP method to measurement of a wide range of flows, ranging from laboratory flows to industrial flows, and to environmental flows, have been implemented. A statistic up to 2006 was thoroughly summarized in [4]. The original and commercialized UVP measurement systems (e.g. UVP monitors, Met-flow S.A. [5]) were based on the UDM method which is a frequency-domain method. Such systems, however, possess some inherent limitations on maximum measurable velocity and depth. Therefore, application of commercial UVP monitors to a more complicated class of flow in fluid mechanics, i.e. two-phase flow, has been limited. Recently Kikura et al. [6, 7], Ihara et al. [8], at the Laboratory for Two-phase Flow Research in Tokyo Institute of Technology (TITECH), have succeeded in developing UVP measurement systems including new type of ultrasonic TDX (i.e. multi-wave TDX), multi-channel pulser/receivers (P/Rs) and analog to digital converter (ADC), and originally developed signal processings which include UDM method, UTDC method and an under-development method which is the phase-difference method, for both single-phase and two-phase flow measurements.

UDM method has been early developed and widely implemented in commercial diagnostic medical ultrasound systems, and in UVP monitors also [1, 9]. UDM estimates the Doppler shift frequency f_d which is used to calculate velocity directly. It is a strong signal processing technique that reduces significantly processing time. This is important especially for early developed electronics. By means of pulse repetition, i.e. a number of pulses are used for calculation of velocity, the possibility to successfully calculate flow velocity (i.e. success rate) can be increased. This is important when signal to noise ratio (SNR) in the test systems is low. Its main disadvantage is aliasing [9], i.e. maximum measurable velocity is limited by repetition frequency F_{prf} of ultrasonic pulses due to Nyquist sampling theorem. In addition, when the number of pulses is increased, the temporal resolution and the frequency of measurement (i.e. frame rate) are decreased. This is usually not expected especially in measurement of highly transient phenomena and turbulence.

UTDC is another signal processing which is based on the cross-correlation of at least two echo signals. It calculates the shift in position of ultrasonic scatterers. Velocity is calculated directly using the shift. Because only two signals are used, temporal resolution of the measurement is high. In addition, since UTDC is a time-domain method, it can explicitly avoid the limitation of maximum measurable velocity set by Nyquist sampling theorem. However, maximum measurable velocity is constrained by the width of ultrasonic beam and F_{prf}. Nevertheless, that constrain generally produces higher maximum measurable velocity compared with that of UDM. Because less number of pulses are used in UTDC, this signal processing offers lower success rate, especially in systems whose SNR is low. That is not expected in practical measurement when there is a lack of ultrasonic scatterers and/or weak echo signal coming back from the flow field [9].

Recently, a UVP method, which is based on the Tokyo Tech's UVP system, for measurement of both single-phase and two-phase flows in a vertical pipe has been developed at the Laboratory for Industrial and Environmental Fluid Dynamics, Institute of Mechanics (IMech), VAST, in Hanoi, Vietnam. The signal processings include both UDM and UTDC. At present, test flows are generated in two flow loops using two vertical pipes of 26 mm I.D. and 50 mm I.D. respectively. Test flows of fluid have downward orientation. The smaller pipe has a large ratio of length to diameter of the pipe. It is exploited for measurement of laminar flow at low Reynolds (Re) number where $Re=UD/\nu$ where U

is the average velocity of liquid at a pipe cross-section; D is the pipe diameter; ν is the kinematic viscosity of liquid. The larger pipe has smaller ratio of pipe length to diameter. It is used for measurement of turbulent single-phase flow at higher Re and for measurement of two-phase flow. For single-phase flow, the range of Re in 50 mm I.D. pipe is from 0 up to around 20,000 at 30 degree Celsius. For two-phase flow, the loop can generate counter-current air-water flow with liquid flowing downward and gas flowing upward in 50 mm I.D. pipe. Such two-phase flow covers all flow patterns including bubble, slug, churn and annular. Such flows are typically encountered in industrial applications such as thermal hydraulic safety of nuclear reactors (e.g. the counter-current flow-limitation problem during re-flooding of nuclear reactors in the case of loss of coolant accident - LOCA), oil-gas production systems (e.g. gas lift technology), bubble columns in chemical engineering etc. [10]. Preliminary practical measurements with the flow loops using UVP and particle image velocimetry (PIV) methods have been carried out [11].

In this study, we applied both UDM and UTDC signal processings, on the same hardware including multi-wave TDX, P/Rs, ADC and PC, for measurements of single-phase and two-phase flows in the flow loops. Measurements have been conducted with different flow regimes of single-phase and two-phase flows. For single-phase flow, two flow patterns have been measured including fully developed laminar flow at $Re = 1{,}400$ (using 26 mm I.D. pipe), and fully developed turbulent flow at $Re = 5{,}300$ (using 50 mm I.D. pipe). Results were compared with those of analytical solution for laminar flow, and of direct numerical simulation (DNS) for turbulent flow. For two-phase flow, measurements were carried out at two different values of Reynolds number of liquid (using 50 mm I.D. pipe). The first one $Re = 5{,}300$ (same as that of single-phase turbulent flow) with relatively low void fraction ($J_L = -103.1$ mm/s; $J_G = 0.1698$ mm/s) where J_L and J_G were superficial velocities of liquid and gas respectively. The second one $Re = 4{,}000$ with higher void fraction ($J_L = -80$ mm/s; $J_G = 2$ mm/s). In the second case, correlation with other published measured data by wire mesh tomography (WMT) method [12] has been conducted. In addition, since UDM can accept different values of number of ultrasonic pulses, measurements of single-phase and two-phase flows were also conducted by setting number of pulses equal to 2, 4, 8, 16, and 32 in UDM. Based on these measurements, investigation of the characteristics of each signal processing has been carried out. Advantages and disadvantages of UDM and UTDC when they are applied to measurement of pipe flow (single-phase and bubbly counter-current two-phase) have been evaluated. Suggestions for the application of UDM and UTDC for measurement of single-phase and two-phase flows have been proposed.

2. SIGNAL PROCESSINGS OF UVP METHOD

Application of ultrasound for measurement of velocity of liquid flow has been originally proposed by Satomura [1]. Regardless of methods of signal processing used, UVP method requires the transmission and reception of radio frequency (RF) ultrasonic signal at pulse repetition frequency F_{prf} (corresponding to the pulse repetition duration $T_{prf} = 1/F_{prf}$). Spatial ranges (i.e. locations where velocity is calculated) are specified using the range-gated time system which calculates the position of measurement channels using the speed of sound in the test fluid and the time instant when the RF echo signal is sampled. In UVP method, spatial range defines the thickness of the measurement volume which is specified by $N\lambda/2$ where N is the number of RF cycles; λ is the wavelength (corresponding to the center frequency f_0) of the ultrasound used. Captured signal is processed using either UDM or UTDC to obtain flow velocity at measurement channels.

2.1. UDM

Presently, UDM is the most widely used signal processing method in UVP systems [2]. In this method, the Doppler shift frequency (f_d) at a measurement channel is extracted by analyzing a number (usually 2^5-2^7) of echo waves from the channel. Due to the movement of the fluid flow (or more precisely the moving of ultrasonic scatterers), f_d is the change in the frequency of the echo signal compared with the emitted signal due to Doppler effect. The relationship between f_d and the fluid velocity v at the channel is expressed in Eq. (1),

$$f_d = 2f_0\frac{v}{c} \tag{1}$$

where f_0 is the center ultrasonic frequency; c is the sound speed in the test fluid.

Theoretically, an echo signal always contains information of f_d. However, it is currently impossible to extract f_d just using one echo wave from a measurement channel due to the limitation of the speed of digitizers. It is therefore a repetition of emitted pulses is needed. As a result, a number of echo waves from a measurement channel are used for the analysis of f_d. Therefore, UDM is more precisely expressed by pulse repetition Doppler method. Various techniques for the estimation of f_d have been devised [2] including early developed zero-crossing technique, Fourier transform technique etc. In this study, the autocorrelation technique was used for calculation of f_d from Doppler signals [13-15]. Although this method only calculates the average value of f_d, it is an accurate, stable and robust technique among other ones [15].

Since Doppler effect occurs only in the sound path direction, if the movement is perpendicular to the sound path, f_d is zero. Therefore, in practical measurements, the TDX must be set inclined an angle θ to the flow direction. The flow velocity is calculated following Eq. (2),

$$v = \frac{f_d}{f_0}\frac{c}{2\cos(\theta)} \tag{2}$$

Since echo signal is received between the emissions of two pulses, the traveling time for the emitted and reflected ultrasound is limited. Beyond some distance (i.e. maximum measurable depth) from the TDX surface, reflected ultrasound can not reach the TDX before the next pulse is emitted. This determines the maximum measurable depth (P_{max}) of UVP method as shown in Eq. (3),

$$P_{\max} < \frac{c}{2F_{prf}} \tag{3}$$

In addition, according to the Nyquist limit, the constrain set on F_{prf} is stated as $F_{prf}/2 > f_d$. As the result, Eq. (4) expresses the maximum measurable velocity,

$$v_{\max} = \frac{cF_{prf}}{4f_0\cos(\theta)} \tag{4}$$

2.2. UTDC

UTDC has been later developed as an advanced signal processing for UVP method [9]. UTDC signal processing calculates the correlation coefficient R using at least two successive echo waves from a measurement channel. Maximum of R corresponds to the match between two time series with a time shift t_d. This means that between two successive pulses (i.e. during T_{prf}), seeding particles in the measurement volume have moved a distance $c \times t_d/2$ in the sound path direction. Number 2 here means that sound has to travel twice (forward and backward) the distance between the TDX and the measurement volume. Hence, the velocity is written as Eq. (5) taking into account the inclined angle θ,

$$v = \frac{c \times t_d}{2T_{prf} \cos(\theta)} \tag{5}$$

The maximum measurable depth of UTDC is exactly the same as that of UDM which is stated in Eq. (3). Theoretically, there is no limit of maximum measurable velocity of UTDC. However, if the velocity is high and T_{prf} is large, particles in a measurement channel at the time the first pulse arrives may completely move out the channel at the time the second pulse arrives. It is impossible to calculate R in that case. Therefore, in UTDC, maximum measurable velocity is related to F_{prf} and the width of ultrasonic beam. High velocity needs high F_{prf} (i.e. small T_{prf}), larger beam width facilitates measurement of higher velocity.

2.3. Main characteristics of UDM and UTDC

General comparisons of UDM and UTDC algorithms for single-phase flow measurement have been carried out in details in Hein et al. [9]. The followings are main characteristics of both methods:

- UDM algorithm usually requires less computation time while UTDC tends to be computationally expensive with much time spent in correlating and searching in the cross-correlation procedure. Initially, UTDC signal processings were used mainly for off-line calculation.

- Generally UDM uses more pulses than UTDC for the calculation of velocity. Therefore, UDM usually has lower temporal resolution and measurement frequency. Of course we can increase F_{prf} to have higher temporal resolution. However, maximum measurable depth is decreased when F_{prf} increases (Eq. 3).

- Maximum measurable velocity of UDM is limited by F_{prf} while that of UTDC is related to the width of ultrasonic beam and to F_{prf}, and is generally higher.

- The longer the pulse width (lower bandwidth), the better the precision of UDM while it is reversed with UTDC.

- UTDC estimates the shift of the position of scatterers while UDM estimates the Doppler shift frequency which is not a single value but a frequency band in real systems. In applications where some factors, other than scatterers' movement, may affect the band of Doppler shift frequency, UDM will have low precision.

Since many pulses are used, UDM usually has higher success rate of velocity calculation, especially at low SNR. This is important in practical measurements when there is a lack of seeding particles in the flow or the flow boundaries do not facilitate well the transmission of ultrasound.

3. APPLICATION OF UVP METHOD TO TWO-PHASE FLOW

Measurement of bubbly two-phase flow using UVP encounters the same phase separation problem when PIV or laser Doppler methods are applied to two-phase flow. It is because, in two-phase flow, ultrasound (as well as light and laser) is reflected from both scatterers and gas-liquid interfaces. That means that captured signal include both data of liquid phase and that of gas phase. In order to obtain information of each phase separately, phase separation techniques are required.

3.1. Multi-wave TDX

Based on the dependency of measured data of two-phase flow on the measurement volume size and ultrasonic scatterers' size, it is possible to measure each phase using a specific ultrasonic frequency and beam size. Detailed investigation by Murakawa et al. [16] has shown that using two ultrasonic beams, 8 MHz with beam diameter 3 mm for liquid and 2 MHz with beam diameter 10 mm for gas, simultaneous measurement of both liquid and gas is possible. Based on this idea, they have successfully developed a uniquely designed TDX, which is referred to as the multi-wave TDX, for two-phase flow measurement. The multi-wave TDX is able to emit and receive two RF ultrasonic signals, 8 MHz and 2 MHz, at the same time and same position. It consists of two separate concentric cylindrical piezo-electric elements. 8 MHz element is located at the center. It is surrounded by 2 MHz component which has an annular shape [16]. A schematic configuration of the multiwave TDX is presented in Fig. 1.

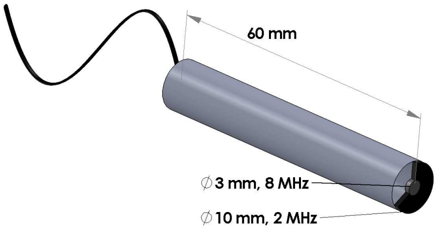

Fig. 1. A schematic configuration of the multiwave ultrasonic TDX

Using this newly developed multi-wave TDX, each frequency connected to a separate commercial UVP monitor, measurement of bubbly two-phase flows was enable. However, synchronization, both time and space, between two separate UVP monitors was difficult since in commercial UVP monitors, maximum measurable depth is linked with F_{prf}. As the result, a two-channel UVP measurement system has been developed in Tokyo Tech. It enables simultaneous measurement of instantaneous velocity profiles of liquid and gas at the same position along the sound path.

However, it is important to note here that, while 2 MHz element can be controlled to mostly eliminate echo signal reflected from scatterers whose size is much smaller than bubble size, 8 MHz element cannot eliminate much stronger echo signal reflected from bubble surfaces. Therefore, using just only the multi-wave TDX, phases are not completely separated.

3.2. Discrimination of gas phase from liquid phase

As mentioned above, measured data of 8 MHz element needs further phase separation in order to obtain instantaneous velocity profiles of liquid and gas. This can be done using measured data of 2 MHz frequency. Since the two elements are synchronized, measured data is obtained at the same time and same positions. If bubbles appear along the measurement line, it will be recognized in the 2 MHz frequency. Since the diameter of the 2 MHz beam is 10 mm which is considerable larger than the typical bubble size (around 4-5 mm) in this study and in industry [17], 2 MHz can capture all bubbles along the sound path. However, bubbles may completely obstruct 8 MHz ultrasound beam. Therefore, measured data behind the closest bubble will be deleted from 8 MHz frequency [18]. This phase separation technique is applied for both UDM and UTDC for two-phase flow measurement. As a result, phase velocities are completely separated.

4. UVP MEASUREMENT SYSTEM, TEST FLOW LOOPS AND EXPERIMENTAL CONDITIONS

4.1. UVP measurement system

The signal processings are implemented into one hardware system for analysis of captured RF signal. They work separately, not in parallel mode. The multi-wave UVP system consists of:

- Multi-wave TDX (Japan Probe Co. Ltd.): 2 MHz and 8 MHz center frequencies for emission and reception of 2 MHz and 8 MHz ultrasonic signal;

- P/Rs (DPR300 and DPR35+, JSR Co., Ltd): Each is connected to one frequency element of the multiwave TDX. Both P/Rs work in synchronization mode. The P/Rs generate negative electric spikes to excite the multi-wave TDX (both frequency elements at the same time) for the generation of ultrasonic pulses at the TDX surface with maximum F_{prf} of 5 kHz, and minimum F_{prf} of 100 Hz. It should be noted here that UDM method is usually used with tone-burst P/Rs which are able to generate electrical pulses of small band of frequency. However, we have proved that using spike P/Rs, which are cheaper and very popular in ultrasonic inspection industry, using appropriate signal setting and appropriately designed ultrasonic TDX, measurement of velocity is also possible [18];

- Two-channel ADC (NI PCI-5112, National Instrument Co. Ltd.): 8 bits resolution; maximum sampling rate 100 MHz; synchronized with both P/Rs for data digitization and acquisition.

- PC (Intel Core i7 CPU, 4 GB RAM, Windows 7 OS): for hosting ADC and signal processings.

4.2. Test flow loops

A sketch of the flow loops for measurement of single-phase and bubbly counter-current two-phase flows is shown in Fig. 2 where: 1: floor tank; 2: needle valve of test pipe 4; 3: air nozzle for bubble generation; 4: large test pipe (Φ50 mm); 5: overflow weir; 6:

water circulation pump; 7: bypass valves; 8: pipe for water supply to the upper tank; 9: overflow weir; 10: upper tank; 11: water box for housing ultrasonic TDXs; 12: multi-wave TDX; 13: water drainage pipe for overflow; 14: water drainage valves; 15: main water drainage pipe of the loops; 16: air compressor; 17: valve for controlling flow-rate of air; 18: regulator of air flow-rate (Cole Parmer Co. Ltd.); 19: air float valve (Tokyo Keiso Co. Ltd.); 20: P/Rs; 21: PC; 22: water flow-meter (Aichi Tokei Co. Ltd.) for test pipe 4; 23: small I.D. test pipe (Φ26 mm); 24: needle valve of test pipe 23.

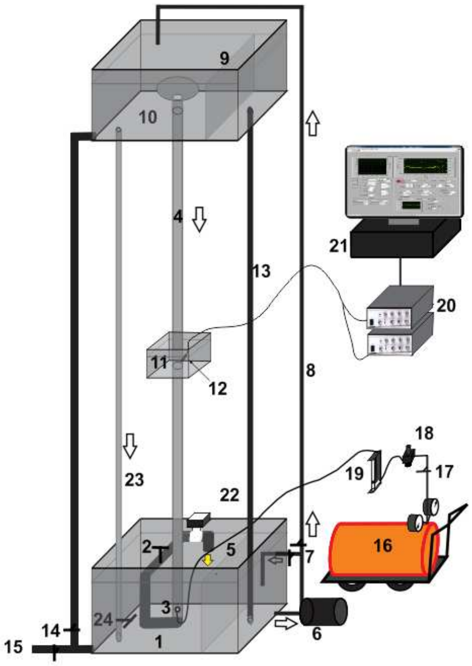

Fig. 2. A sketch of the experimental flow loops in the Laboratory for Industrial and Environmental Fluid Dynamics of IMech, VAST

As shown in Fig. 2, there are two flow loops using two vertical test pipes: large test pipe 4 with I.D. 50 mm, 3 m long and small test pipe 23 with I.D. 26 mm, 2.3 m long. Both are made of transparent acrylic that facilitates UVP measurement and optical flow visualization. Because the ratio of pipe length to pipe I.D. of large test pipe 4 is not enough for fully developed laminar flow, it was used for measurement of fully developed turbulent single-phase flow and two-phase flow. Small test pipe 23 has higher ratio of pipe length to pipe I.D., it was used for measurement of fully developed laminar single-phase flow. Water flow-rate in the test pipe 4 was controlled by a needle-type valve located at the outlet of the pipe, and was measured using a high-precision turbine flow-meter. A funnel was attached to the inlet of test pipe 4 to facilitate the fully developed state of the flow in the pipe (Fig. 2). For test pipe 23, a commercial ultrasonic flowmeter KATflow200 (Katronic Technologies Ltd.) was used for measurement of flow-rate. The flow-rate was controlled by a needle valve 24. Overflow weirs in water tanks ensure a constant pressure difference between the tanks. For bubbly counter-current flow, bubbles are generated at the bottom part of the test pipe 4, and rise up. Water flows down from the upper tank to the lower tank solely under the effect of gravity.

For test pipe 4, the multi-wave TDX was housed in a water box surrounding the test pipe. The position of the water box can be varied with L/D where L is the inlet length and D is the pipe I.D. For test pipe 23, the TDX was submerged in the floor tank at $L/D = 53$. In addition the water box can also be used for optical visualization and for PIV method.

4.3. Experimental setup

The multi-wave TDX was fixed at an inclined angle of 45 degree to the main flow direction [19] using a TDX holder. The optimum inclined angle of 45 degree of the ultrasonic TDX was investigated by Murakawa et al. [19]. The thickness of pipe wall at the measurement locations was 1 mm. Nylon powder (WS-200P, Daicel-Evonic, Ltd.) with average particle diameter 80 μm, density 1.02 g/cm^3 was used as ultrasonic scatterers for measurement of liquid velocity.

Measurements were carried out at room temperature of around 30 degree Celsius. The liquid temperature was monitored using both digital and mercury thermometers. Sound speed in the liquid was set at 1,500 m/s in the UVP software interface. The number of RF cycles in single-phase flow measurement of liquid using 8 MHz ultrasound was 8 ($N = 8$). For two-phase flow measurement of liquid and gas, $N = 8$ for 8 MHz frequency and $N = 2$ for 2 MHz frequency. As a result, the thickness of measurement volumes of both 8 MHz and 2 MHz channels are the same, i.e. 0.75 mm in the sound path direction. This also enables measurement of liquid and gas at the same position. With this setting, the number of measurement channels of velocity profiles of gas and liquid inside test pipe 4 was 94. For test pipe 23, that number was 49.

Auto-correlation algorithm was used to analyze f_d and to calculate fluid velocity. Using this algorithm, the required number of ultrasonic pulses could be any integer greater than 1. This enabled further assessment of UDM signal processing.

4.4. Experimental conditions

Measurements have been carried out for both single-phase and bubbly two-phase flows in the test pipes. All measurements have been carried out for fully developed flow regimes. The system pressure was atmospheric pressure.

For single-phase flow, measurements were conducted with fully developed laminar flow at $Re = 1{,}400$ using test pipe 23. Measured results was compared with the analytical solution (i.e. parabolic profile) of fully developed laminar flow in a pipe. For fully developed turbulent flow regime, measurements were carried out at $Re = 5{,}300$ using test pipe 4. In the latter case, measured result was compared with that of DNS simulation [20].

For two-phase flow, measurements were carried out in bubbly flow pattern and at low void fraction conditions. In this case, test pipe 4 was used. Using UVP method for bubbly two-phase flows, a void fraction less than 10% is usually adopted [21]. Higher void fraction in bubbly flow condition will cause excessive multiple reflection of ultrasound and the results will not be reliable. Typical average bubble diameter in this study was around 4-5 mm which is in accordance with previous research using multi-wave TDX.

Two cases of bubbly flow correspond to two different pairs of superficial velocities of liquid and gas have been measured. In the first case, $J_L = -103.1$ mm/s ($Re_{liquid} = 5,300$ same as single-phase flow measurement); $J_G = 0.1698$ mm/s. In the second case, $J_L = -80$ mm/s ($Re_{liquid} = 4,000$); $J_G = 2$ mm/s. This was one of the measurements reported by Fuangworawong et al. [12] using WMT.

5. EXPERIMENTAL RESULTS

5.1. Measurement of single-phase flow

For single-phase flow, only 8 MHz element of the multi-wave TDX was used. Measured results using both UDM and UTDC for fully developed laminar flow in the small test pipe 23 are shown in Fig. 3. Reynolds number in this case was around 1,400. As shown in Fig. 3, both UDM and UTDC can be applied to measurement of laminar flow at low Reynolds number. Measured results by both methods agree well with analytical solution, i.e. the radial parabolic profile of axial velocity, of laminar pipe flow. However, close to the wall, velocity at some measurement channels are lower estimated by both UDM and UTDC, as compared with the parabolic velocity profile of the exact solution. The same situation happened with measurement of turbulent pipe flow. Explanation will be given later on for both laminar and turbulent flow measurements.

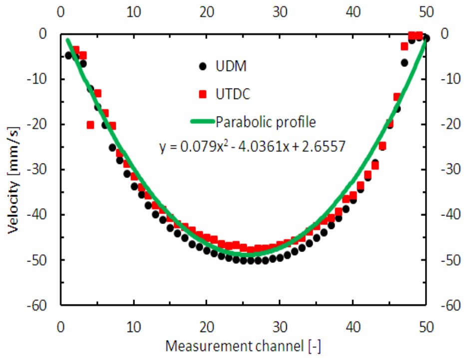

Fig. 3. Velocity profiles of fully developed laminar pipe flow using UDM, UTDC and parabolic profile of the analytical solution

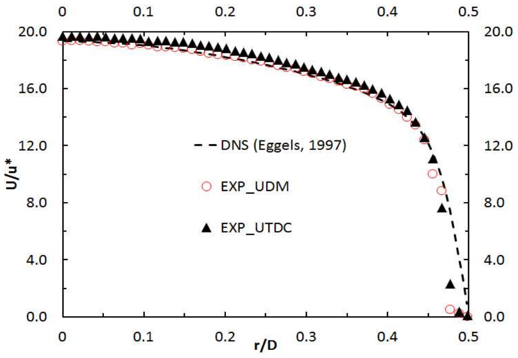

Fig. 4. Comparison between measured results using UDM, UTDC and DNS result

For measurement of fully developed turbulent pipe flow, either pipe, pipe 4 or pipe 23 could be used. The larger diameter one, pipe 4, was selected since, currently in our system, two-phase flow could only be generated in the larger pipe 4. Comparison of time averaged velocity profiles normalized by shear velocity, of UDM, UTDC and DNS [20] is shown in Fig. 4 (where r is the radius from the pipe center; D is pipe diameter; U is axial velocity at a channel; u^* is the shear velocity). Note that the sign of velocity was reversed to positive to comply with the published data.

As shown in Fig. 4, both UDM and UTDC results mostly agree well with DNS result which was calibrated with other measurement methods (PIV, LDA, HWA etc.) [20].

However, close to the wall, the same situation happened as in the measurement of laminar flow. There exists some deviation between the result of DNS and measured results using UVP method. As anticipated, UVP method lower estimates velocity of liquid close to the wall. This is due to the effect of the measurement volume size of UVP method [22]. As shown in Fig. 5, measurement volume of UVP method is defined by the diameter of the piezo-electric element of the TDX (beam size) and the thickness $N\lambda/2$ (i.e. 0.75 mm with this experimental conditions). The wall thickness at the measurement positions of both pipes were all 1 mm. Close to the pipe wall, measurement volumes 1 to 5 are all influenced by the wall and outside liquid which were not moving. Therefore, calculated velocity of these volumes would be decreased. This agreed well with measured results by UDM and UTDC shown in Fig. 3 and Fig. 4.

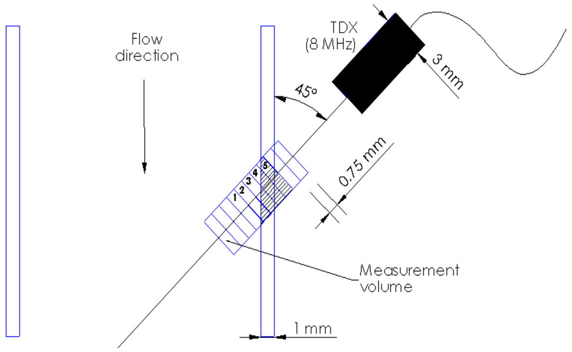

Fig. 5. Effect of measurement volume size on measured velocity close to the wall in UVP method

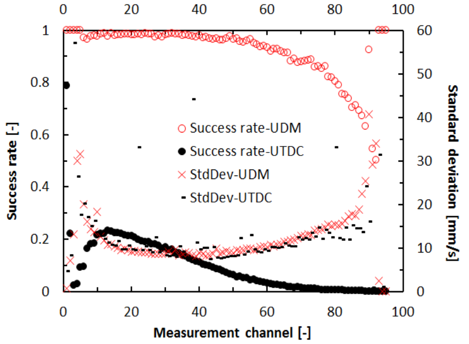

Fig. 6. Radial profiles (along the diameter of the large test pipe) of the success rates of UDM and UTDC

Since UTDC theoretically uses only two echo waves for the calculation of velocity at a measurement channel, its temporal resolution was much higher than that of UDM. In this measurement of turbulent flow, UDM calculation used 128 echo waves for one calculation of velocity at a channel. Therefore, total time for calculation of one velocity profile by UTDC and UDM were 40 ms and 240 ms respectively. This was observed during measurement of turbulent single-phase flow using these signal processings with our hardware system.

In contrast, Fig. 6 shows the success rate, which was defined as the ratio of the number of successful calculations of velocity at a channel to the total number of velocity profiles in one measurement, of UTDC and UDM. The success rate was calculated at each measurement channel along the measurement line for the same flow conditions and the same level of standard deviation of measured velocities. The success rate of UDM was obviously several times as high as that of UTDC at all measurement channels taking into account that, standard deviations were almost the same between UDM and UTDC.

5.2. Measurement of bubbly counter-current flow

(1) Low void fraction condition

A typical bubble image of the flow at this condition is presented in Fig. 7. The image was captured using a high speed camera (JVC Hybrid Camera GC-PX1, JVC Co. Ltd.) with frame rate 300 Hz.

Simultaneous measurements of liquid velocity and gas velocity have been carried out using UDM and UTDC at the same flow condition. In order to obtain instantaneous velocity profiles of both liquid and gas, the phase separation technique proposed above (section 3) has been applied. Measured results in the case of relatively low void fraction ($J_L = -103.1$ mm/s, $Re_{liquid} = 5{,}300$; $J_G = 0.1698$ mm/s) are shown in Figs. 8 and 9. Fig. 8 shows time average velocity profiles (from pipe center) of both phases based on instantaneous velocity profiles. The results of both methods are comparable.

Fig. 7. A typical bubble image at low void fraction condition captured using high speed camera

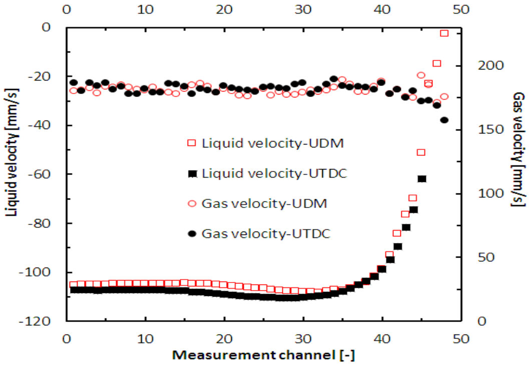

Fig. 8. Radial time-averaged measured velocity profiles (along the radius of the large test pipe) of liquid and gas velocity by UDM and UTDC

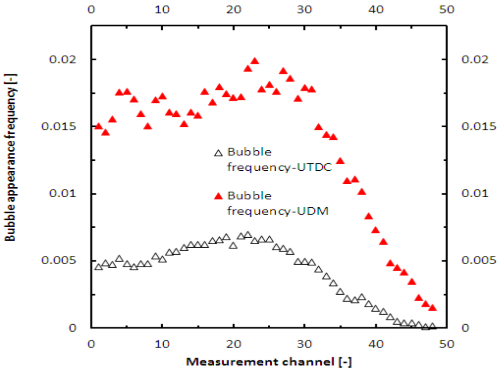

Fig. 9. Measured profiles (along the radius of the large test pipe) of bubble frequency by UDM and UTDC

Based on the measured velocity profiles of gas phase by 2 MHz frequency, a profile of local frequency of the appearance of bubbles at measurement channels (bubble appearance frequency or bubble frequency) was obtained. Since the success rate of UDM was considerably higher that of UTDC, bubble frequency measured by UDM (with 32 ultrasonic pulses used for one calculation of velocity in this measurement) was much higher than that of UTDC (basically 2 pulses were used) as shown in Fig. 9. It is currently difficult to evaluate exactly the success rates of UDM and UTDC since they strongly depend on UVP parameter settings such as signal gain, filter threshold, flow conditions etc. Here higher bubble frequency by UDM must be effected by the number of pulses used. Surely, more signals reflected from bubbles were accumulated during 32 pulses in UDM as compared with 2 pulses in UTDC. This absolutely increases the bubble frequency by UDM.

It is well-known that local void fraction can be defined as the probability of the existence of the gas phase at a position in the flow field. It was assumed that the local void fraction distribution was proportional to the bubble frequency at a channel [23]. Therefore, as suggested in Fig. 9, the phase distribution pattern in this case would be intermediate peak [24]. In this low void fraction condition, measured results of bubble frequency by both methods exhibit the same tendency (but not exactly match) as shown in Fig. 9. It was expected that if UDM and UTDC used a same number of pulses, and had same success rate, the bubble frequencies in Fig. 9 should be coincident with each other.

(2) High void fraction condition

In order to further assess the measured results of the distribution of bubble frequency, results measured by 2 MHz frequency (using both UDM with varied number of pulses and UTDC) were correlated with the local void fraction profile measured at the same flow condition by Fuangworawong et al. [12] using WMT. In this case ($J_L = -80$ mm/s; $J_G = 2$ mm/s), flow regime was found to be core-peak by using WMT. Measurements using UDM were conducted with the number of pulses 2, 4, 8, 16 and 32.

A typical bubble image of this flow condition is presented in Fig. 10.

Fig. 10. A typical bubble image at high void fraction condition captured using high speed camera

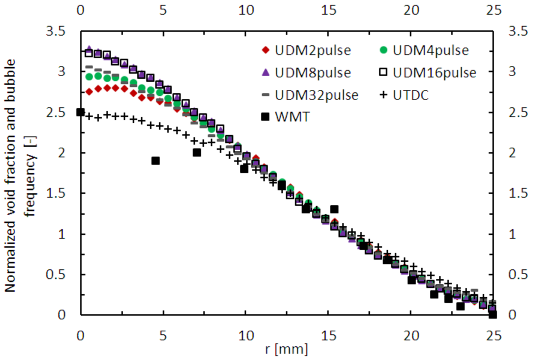

Fig. 11. Measured profiles (along the radius of the large test pipe) of normalized void fraction using WMT and normalized bubble frequency using UDM and UTDC

As shown in Fig. 11, the result measured by WMT was normalized void fraction at $L/D = 22$. Therefore, the measured results of bubble frequency by UDM and UTDC (at almost same measurement position) shown here must also be normalized. For each measurement, measured bubble frequency at a channel was normalized by dividing the bubble frequency by P_{total}. Here P_{total} was the integration of bubble frequency of the measurement over the pipe cross-section at the measurement position. The integration was calculated based on the profile of bubble frequency of each measurement and the flow area corresponding to each measurement channel, i.e. $P_{total} = \Sigma P_i S_i$ where P_i was the bubble frequency at a measurement channel and S_i was the annular area of the flow corresponding the channel.

It can be seen that, all measured results of UDM and UTDC exhibited the same core-peak patterns as that measured by WMT. The normalized bubble frequencies by both UDM and UTDC were close to the normalized void fraction by WMT. Based on the bubble frequency, the phase distribution patterns of bubbly two-phase flow (i.e. core-peak, intermediate-peak or wall-peak) can be characterized. In addition, local void fraction could be inferred if the exact bubble frequency at the cross-section is known.

6. DISCUSSIONS

6.1. UDM and UTDC for single-phase flow measurement

In the case of single-phase flow measurement, averaged results of both UDM and UTDC were comparable. Application of UDM seems to be more flexible since it can measure velocity profiles at low SNR. Moreover, test measurements have been conducted with number of pulses as small as 2, 4, 8 and 16. Both instantaneous and averaged velocity profiles were successfully obtained. At small number of ultrasonic pulses, UDM was able to give significantly high frame rate, around 200 Hz in our system, and high temporal resolution of measurement. However, to maintain small standard deviation of the results, higher number of pulses is usually needed (e.g. 32, 64, 128... pulses). In such cases, UDM offers higher success rate while UTDC offers higher frame rate and temporal resolution. In addition, some previous research claimed that UTDC tends to be a quantitative flow measurement while UDM tends to be qualitative one [9]. Both UDM and UTDC suffer from wall effect. Measured results close to the wall are under-estimated.

UDM is applicable for smaller range of Reynolds number. On our system, maximum F_{prf} is 5 kHz. If the inclined angle is fixed at 45 degree for the best TDX arrangement, maximum Reynolds number for UDM is around 40,000 (at 30 degree Celsius) if the double-range option (which specifies unidirectional flow) is used. This estimation is based on Eq. (4) which gives maximum measurable velocity of 8 MHz frequency about 663 mm/s. It means that for bidirectional flows, maximum Reynolds number for UDM can only be around 20,000 at 30 degree Celsius. While maximum Reynolds number of UTDC, which we estimated based on the width of measurement channel of 0.75 mm and F_{prf} 5 kHz, would be up to around 330,000 at the same temperature. That was estimated based on the assumption that UTDC is able to estimate velocity as long as between two pulses, particles do not completely move vertically out of the measurement volume (Fig. 5) [9]. In details, during $T_{prf} = 1/5{,}000$ s, maximum distance that particles can move in vertical direction is $0.75\sqrt{2}$ mm. This leads to the maximum measurable velocity around 5,300 mm/s.

6.2. Two-phase flow measurement

For counter-current flow, bubble velocity is generally smaller than that in stagnant water column. Experiments (e.g. [25]) have shown that in stagnant water column, both instantaneous and terminal rise velocities of bubbles of the size 1 mm to 10 mm were in the range from 100 mm/s to 300 mm/s. In our UVP system, the absolute values of maximum measurable velocities of 2 MHz channel of UDM (with bidirectional-flow option) is 1,325 mm/s. That of UTDC is estimated around 5,303 mm/s. Therefore, for counter-current flow, UDM and UTDC do not suffer from aliasing problem for gas phase measurement. However, for co-current two-phase flows (especially in co-current upward flow where bubbles rise in the same direction and faster than liquid), UDM may be easier to suffer from aliasing problem. In addition, in two-phase flow, if void fraction increases, instantaneous velocity of liquid will increase. As a result, in UDM method, there is a possibility that maximum liquid velocity can exceed maximum measurable velocity of liquid phase of 8 MHz frequency, which is only one fourth of the maximum measurable velocity of gas phase of 2 MHz frequency. In two-phase flow measurement, bidirectional-flow option must be used. Hence, the absolute value of the maximum measurable velocity of liquid phase of 8 MHz frequency is just about 331 mm/s in our system. Therefore, care must be taken regarding the aliasing problem in measurement of instantaneous liquid velocity of two-phase flow at high void fraction using UDM.

About the measurement of gas phase, when the number of pulses used in UDM increase, the bubble frequency will increase as explained in section 5.2. This phenomenon is identical to the capture of streak images in flow visualization. If the exposure time is long, many particles will be captured in a single image. In UDM, if too many pulses are used for calculation of the velocity of two-phase flow, bubble frequency will approach to 1 easily (especially at high void fraction condtion). Therefore, in order to obtain more precise instantaneous bubble frequency for calculation of local void fraction, less number of pulses are preferable. That is why in Fig. 11, UTDC result seems very close to that of WMT. It should be noted here that though UDM calculation using only two pulses (UDM2pulse curve in Fig. 11) had the same temporal resolution with that of UTDC, its success rate was questionable since too few pulses were used for velocity calculation.

7. CONCLUSIONS

A UVP measurement method for two-phase flow has been developed. The signal processings include UDM and UTDC. To clarify the characteristics of each signal processing, they have been applied to measurements of single-phase (fully developed laminar and turbulent) and two-phase (bubbly counter-current) flows in vertical pipes.

For single-phase flow measurement, good agreement between the results of UDM, UTDC and analytical solution for laminar flow, and DNS for turbulent flow has been obtained. Some deviation of the UVP results close to the wall was observed and explained. It is possible to correct UVP results close to the wall by using the parabolic velocity profile or using DNS data of pipe flow. In addition, the measured results showed that at the same standard deviation of velocity, the success rate of UDM was much higher than that of UTDC. However, as a tradeoff, the temporal resolution of UDM was considerably lower than that of UTDC.

For two-phase flow, both methods have been successfully applied to the measurement of liquid and gas velocity of bubbly counter-current flow. Both instantaneous and time-average velocity profiles have been obtained. Based on instantaneous velocity profiles of both phases, drift velocity between liquid and gas can be calculated. Moreover, phase distribution patterns can be addressed based on the pattern of profile of bubble frequency. In addition, local void fraction profile could be inferred from the bubble frequency. However, the bubble frequency depends on the success rate of bubble velocity measurement. In addition, the success rate may change along the measurement line. If the success rate of the measurement of the gas phase of each method can be estimated exactly, local void fraction profile can be evaluated exactly. In addition, UDM can be applied to a smaller range of *Re* number (both single-phase and two-phase) while UTDC can be applied to a much wider range.

ACKNOWLEDGEMENT

The first author is grateful to Japan Society for the Promotion of Science - JSPS (within the framework of the JSPS Ronpaku - dissertation PhD program) and the scientific research project VAST01.01/13-14 of VAST for financial support to carry out this research.

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Received June 24, 2013

VIETNAM ACADEMY OF SCIENCE AND TECHNOLOGY
VIETNAM JOURNAL OF MECHANICS VOLUME 35, N. 3, 2013

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