Development of Two-dimensional Vector UVP with Phased Array Technique

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Phased array ultrasonic velocity profiler is developed in this study. Phased array ultrasonic technique is widely used in nondestructive evaluations and medical applications. Phased array technique requires multi-channel transducer and pulser receiver. According to geometry arrangement of the transducer, ultrasonic pulser apply pulse excitation with certain time delays to focus ultrasonic beam to the designated angle. This electric scanning is performed in different steering angles. Consequently, two dimensional measurement can be performed without changing the transducer installation. For each measurement lines, two velocity profiles are measured simultaneously. Whole elements are used for ultrasonic excitation and selected two elements are used as receiver. Since two elements are placed in different position, measured velocity profiles are different as well. Therefore, two-dimensional vector can be reconstructed by solving the geometry matrix. Engineering application for fluid flow measurement is demonstrated successfully using the developed system.

Keywords: Ultrasound, Phased Array, Flow Mapping, CFD, Swirling Flow

1. Introduction

Ultrasonic Velocity Profiler (UVP) method can be used for flow mapping in channel flow. In UVP method, instantaneous velocity profiles of fluid on measurement line can be obtained by analyzing echo signals, which are reflected from particles in the fluid [1]. In addition, UVP can be applied in opaque channel and it is non-intrusive measurement method. Takeda and Kikura [2] investigated velocity field of the mercury flow using UVP. Flow mapping was accomplished either by using multiple transducers (at least 24 transducers was needed for velocity field measurements in order to get good spatial resolution [3]), which were arranged in different positions, or by using single transducer which was moved mechanically through multiple positions and set to multiple angles. However, by using those two techniques, the measurement system becomes larger as the number of transducers increase. Furthermore, the spatial accuracy becomes lower if the transducer is moved mechanically. Three-dimensional velocity flow mapping also can be accomplished by UVP method. The concept and the idea of velocity field flow mapping by UVP was proposed by Lemmin, U. [4] and later developed by Ohbayashi, H. [5]. Measurement system consists of a central emitter, symmetrically surrounded by three receivers, R1 to R3. An ultrasonic pulse is emitted into fluid from the emitter, and the surrounding receiver receives the echo reflected from tracer particles. By analyzing these received echo waves, three directional velocity components can be obtained in the same manner as in the conventional UVP for each receivers and three-dimensional velocity vector can be formed. Recently, velocity vector measurement using phased array sensor had been developed by Hamdani [6].

This paper presents the development of two-dimensional velocity vector using phased array sensor. To overcome such problems in conventional UVP (multiple sensors and mechanical movement), an array sensor, which has multiple ultrasonic elements, can be used. By using the array sensor, velocity profiles on multiple measurement lines can be obtained with only one sensor. This technique is applied in pipe flow with twisted-tape inserted for investigating the velocity field in single-phase swirling flow. In addition, the measurement technique is used for CFD validation in swirling flow.

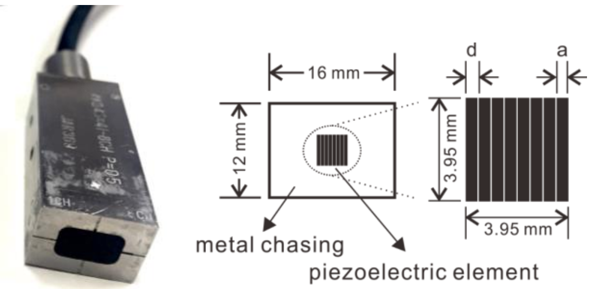
2. Sensor and Phased Array UVP

2.1 Hardware and Software

Phased array sensor has 8 elements with basic frequency 4 MHz and it is shown in Fig 1. Those elements are individually excited by electric pulses and it is controlled by 8-channel pulser/receiver (JPR-10C-8CH, Japan Probe Co., ltd.) with specific delay times. The steering angle and focal point of ultrasonic beam can be changed by controlling the time delay. The beam steering principle is used to control the ultrasonic beam direction. Figure 2 shows the pattern of ultrasonic beam. When the excited element emits rectangular ultrasonic wave, the interference of wave fronts was occurred. Thus, the pattern of the interference depends on the time delay. The steering angle θ and the time delay Δt is related with the speed of sound in a medium c and inter-element spacing d as:

$$\theta = \sin^{-1}\left(\frac{c\Delta t}{d}\right) \quad (1)$$

Figure 3 shows a phased array UVP system. The phased array UVP consists of eight elements linear array sensor, 8-channel pulser/receiver (JPR-10C-8CH, Japan Probe Co., ltd.), A/D converter (NI PXI-5114, National Instruments) and PC. The 8-channel pulser/receiver is used to control the pulse emission from the array sensor. This pulser/receiver generates a rectangle pulse wave signal (measurement volume is, width = 0.74 mm and length = 3.95 mm), and can set these parameters to each element: basic frequency, impressed voltage, wave cycles per pulse, gain, time delay, usage of high-pass and low-pass filter. The digitized signal is transferred to the PC through a PXI system (PXI-1033 National Instruments Inc.), where all signal processing is performed digitally using LabVIEW^{TM} 2011. The spatial and temporal resolution of phased array UVP is 0.74 mm and 32 ms.



(a) (b)

Figure 1: (a). Phased array sensor, 4 MHz and 8 elements. (b). Geometry of phased array sensor (d = 0.5 mm, a = 0.45 mm).

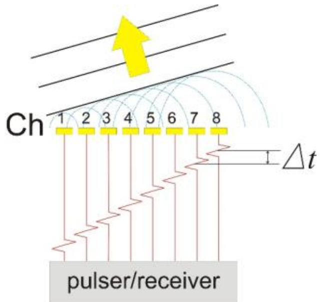


Figure 2: Beam steering technique by emitting pulse on each element with time delay (Δt).

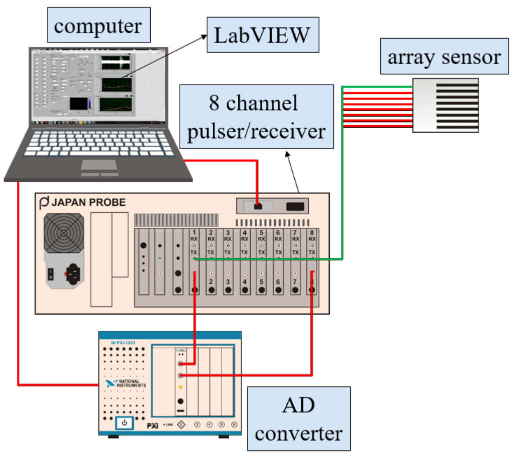


Figure 3: Phased array UVP system.

2.2 Vector Reconstruction

Schematic of the velocity vector reconstruction method with one linear array sensor is shown in Fig. 4. Ultrasonic pulse is emitted from array sensor and each element in the array sensor receives the echo reflected from the surface of particle in the measurement line. The Doppler frequency observed at each element is described as:

$$f_{Di} = \frac{f_0}{c}\left(\vec{e_e} + \vec{e_i}\right).\vec{V} \tag{2}$$

where f_{Di} is the Doppler frequency which is observed at i_{th}-channel element $\vec{e_e}$ is the unit vector in the opposite direction to the emitted beam, $\vec{e_i}$ is the unit vector in direction from particle to i_{th} -channel element and $\vec{V}$ is the particle velocity. From equation (2), the Doppler shift frequency, which is observed in each element, is different due to the difference of element position.

Using reflections recorded by 1[st] and 8[th] elements, as shown in Fig. 4, the particle velocity can be obtained as follows:

$$\vec{V} = \frac{c}{f_0}\begin{bmatrix} \vec{e_e} & + & \vec{e_1} \\ \vec{e_e} & + & \vec{e_8} \end{bmatrix}^{-1}\begin{bmatrix} f_{D1} \\ f_{D2} \end{bmatrix} \tag{3}$$

Therefore, velocity vector in measurement point can be calculated by analyzing the echoes received by different elements in array sensor. Moreover, velocity vector distribution on measurement line can be obtained using this processing at each measurement point. Applying the phased array technique, flow mapping can be conducted with only one array sensor.

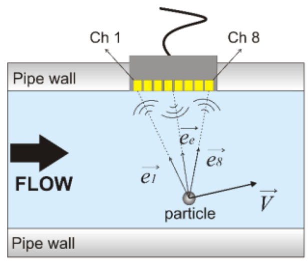


Figure 4: Velocity vector reconstruction with a linear array sensor.

2.3 Doppler Shift Frequency Estimation

The Doppler-shift frequency is calculated by using autocorrelation method. One velocity profile is obtained from several echo signals. The quadrature detection is applied to the received echoes. The signals, which contain Doppler shift frequency, pass the low pass filter, and the information of Doppler-shift frequency remains in the signal because the Doppler-shift frequency is small enough to be separated from the original signal by the low pass filter. The complex envelope signal $z(\tau)$ after the low pass filter is expressed as:

$$z(\tau) = I(\tau) + jQ(\tau) \tag{4}$$

where $I(\tau)$ and $Q(\tau)$ are the in-phase signal and the quadrature phase signal with the received signal respectively. The autocorrelation function R is expressed as:

$$\begin{aligned} R\left(T_{prf},\tau\right) &= \int z(\tau)\times z^{*}\left(\tau - T_{prf}\right)d\tau \\ &= R_x\left(T_{prf},\tau\right) + jR_y\left(T_{prf},\tau\right) \end{aligned} \tag{5}$$

where $Tprf$ is the time between two subsequent pulse emission, $z^*(\tau)$ is the conjugate complex signal of $z(\tau)$, and Rx and Ry are the real and imaginary parts of R, respectively. The phase difference φ between consecutive echo signals is expressed as:

$$\varphi\left(T_{prf},\tau\right)=\tan^{-1}\frac{R_y\left(T_{prf},\tau\right)}{R_x\left(T_{prf},\tau\right)} \tag{6}$$

Doppler shift frequency f_D is obtained as follows:

$$f_D=\frac{1}{2\pi T_{prf}}\tan^{-1}\frac{R_y\left(T_{prf},\tau\right)}{R_x\left(T_{prf},\tau\right)} \tag{7}$$

Thus, a velocity profile can be obtained by analyzing the echo and calculating instantaneous frequencies at each instant.

3. Measurements in Swirling Flow and CFD Validation

To demonstrate the capabilities of Phased Array UVP (PAUVP), a single-phase swirling flow is prepared. Figure 5 shows a simplified measurement set up in pipe with inner diameter 20 mm and twisted tape inserted with twist ratio 3. The measurement of 2D velocity field is performed in different Reynolds number at same position. Phased array sensor is installed perpendicular to the flow and there is no gap, between sensor and liquid, as shown in Fig. 6, in order to measure tangential velocity.

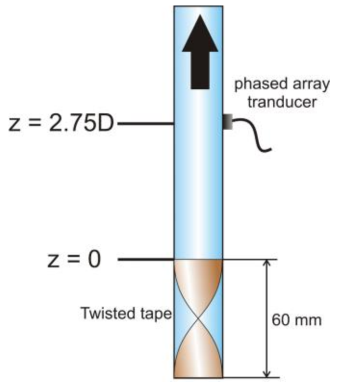


Figure 5: Simplified measurement set up in single-phase swirling flow.

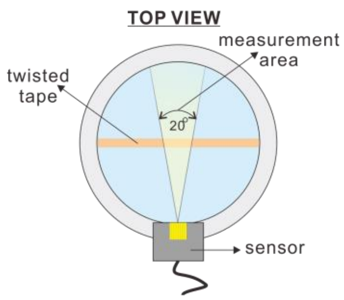


Figure 6: Set up of phased array transducer for tangential velocity measurement.

The numerical simulation is performed with the model geometry scaled to the size of the experimental model. The structure grid for computational domains is generated by using commercial software GAMBIT v.2.2.30 as shown in Fig 7. The test section geometry with 20 mm diameter and 620 mm in length. Twist ratio of twisted tape is three, 420 mm in length and 1 mm thickness. Two model of twisted is made; symmetric and asymmetric model. For asymmetric model, 5° inclination of twisted tape is modelled.

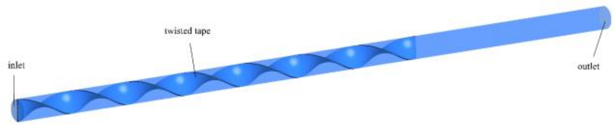


Figure 7: Model domain with twisted tape inserted.

Three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations are solved by commercial CFD code FLUENT® v.14.5. Simulations are carried out on Windows 7, Intel® Core™ i7 3.40 GHz with RAM memory 8 GB.

Two-dimensional velocity field visualization for different *Re* (10000, 14000, and 18000) is done at z/D=2.75. Figure 8 presents the velocity field comparison between experiment (top images) and simulation (bottom images) results. Swirling core position both experimental and numerical does not change for different Reynolds number. Numerical results show that swirling core position is located in the center. On the other hand, experimental results show that swirling core position is not located exactly in the center. It is due to unsymmetrical geometry of twisted tape leads to unsymmetrical flow.

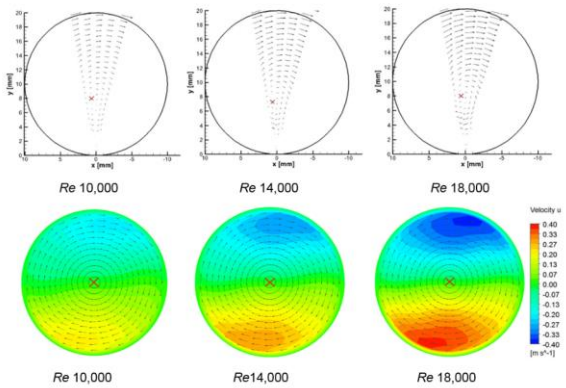


Figure 8: 2D tangential velocity field experiment and CFD at different *Re*.

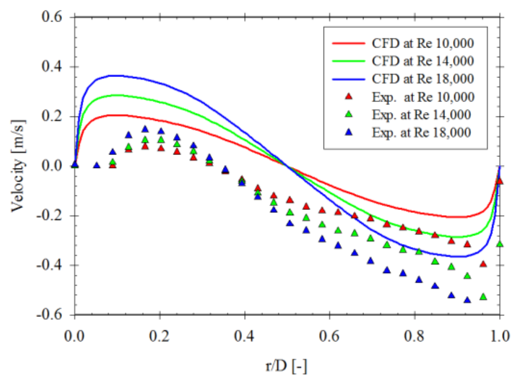


Figure 9: Tangential velocity experiment and CFD at different *Re*.

Quantitative comparison between experiment and CFD is done for tangential velocity at different Reynolds number, as shown in Fig 9. The qualitative comparison of tangential velocity between experiment and CFD, at different Reynolds number shows no good agreement. Therefore, qualitative comparison is needed in case different location of swirling core position.

The discrepancy between numerical and results might be due to the unsymmetrical geometry in experimental apparatus (twisted tape) as shown in Fig. 10. To analyze this problem, unsymmetrical geometry with 5° (same as experiment) and 20° are made in CFD model. Figure 11 shows the comparison of swirling core position between CFD and experiment at different axial position for *Re* 14,000. It can be seen that it is very difficult to get same core position in CFD. As a result, qualitative comparison is done by shifting the core position in CFD result to core position in experiment result. The swirling core position which is detected by PAUVP measurement is used for shifting the data in CFD. A good agreement between CFD and experiment is achieved when CFD data is shifted as shown in Fig. 12, Fig. 13 and Fig. 14.

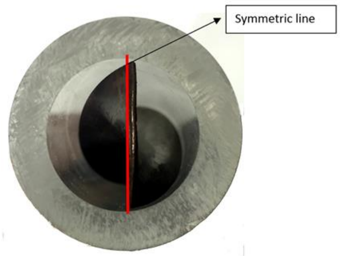


Figure 10: Unsymmetrical geometry of twisted tape (experiment).

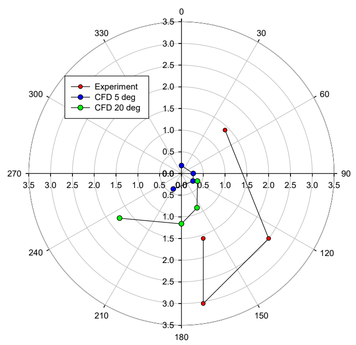


Figure 11: Swirling core position CFD vs experiment.

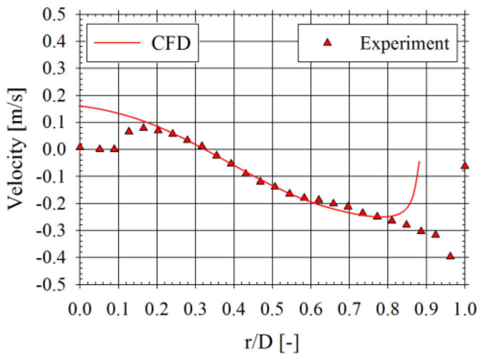


Figure 12: Tangential velocity for Re 10,000 at 2.75D (CFD vs experiment).

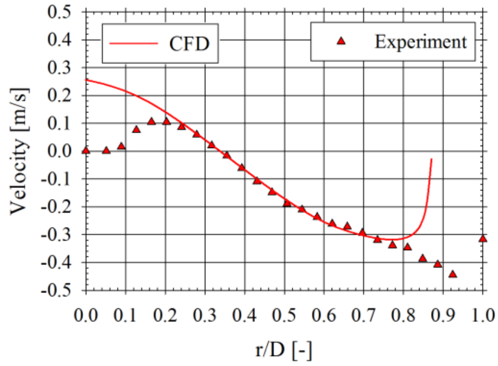


Figure 13: Tangential velocity for Re 14,000 at 2.75D (CFD vs experiment).

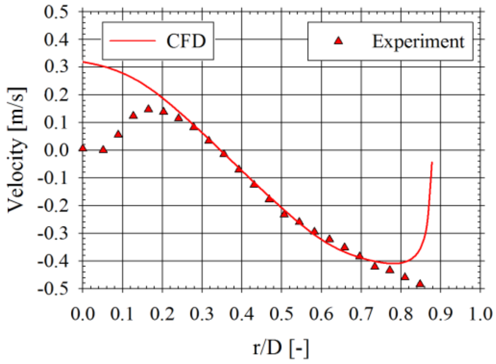


Figure 14: Tangential velocity for Re 14,000 at 2.75D (CFD vs experiment).

4. Summary

Two-dimensional velocity filed measurement has been successfully developed using phased-array technique. This measurement technique has been tested for measuring 2D velocity field in swirling pipe flow. Experimental data are used for validation commercial CFD code FLUENT in single-phase swirling flow. It is concluded that swirling core position in experimental data is needed for a correction in CFD investigation.

References

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