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Estimation of 2D Velocity Vector Fields by Ultrasonic Doppler Velocimetry and Echography

Koki SAWADA, Megumi AKASHI, Hyun Jin PARK, Yuji TASAKA, and Yuichi MURAI
Graduate School of Engineering, Hokkaido University, N13W8, Sapporo 060-8628, Japan

This study aims to establish novel methodology to estimate 2D velocity vector fields with limited number of measurement lines of UVP. To obtain velocity components perpendicular to the measurement line, particles with two-different-diameters are used; the velocity components are measured by particle-tracking-type velocimetry with echo intensity on the larger particles (sufficiently larger than the wavelength of ultrasound), while velocity components in the measurement line direction are obtained by Doppler velocimetry with the smaller particles. As results of the extended measurement above, velocity vector fields with dense one-directional velocity information along the measurement line and coarse information of the component perpendicular to the line are obtained. The coarse information on the present measurement results is supplemented using interpolation method to estimate 2D velocity vector fields from knowledge of particle tracking velocimetry (PTV). Interpolated velocity vector fields take further correction obeying equation of continuity for 2D incompressible flows. Benchmark tests on simple quasi-2D circulating flow in a thin square container indicated that the present methodology works well to estimate, at least, steady, quasi-2D flow fields.

Keywords: echo intensity, multi-directional velocity components, flow field measurement

1. Introduction

Ultrasonic velocity profiler (UVP) [1] has been used for velocity field measurements on opaque liquids such as liquid metal [2-3] and food [4] because of its relatively high temporal and spatial resolution. UVP provides however only one-directional velocity components parallel to the measurement line, and they would be insufficient to discuss characteristics of the field in comparison with multi-directional velocity components obtained by Particle Imaging Velocimetry (PIV) used for measurements of transparent fluids. Using multiple ultrasonic transducers (TDXs) or an array of TDXs can provide multi-directional velocity components at intersections of the measurement lines [5]. The number of velocity vectors is therefore determined by the number of TDXs, and velocity information with the fine spatial resolutions by original UVP measurements has not been used efficiently. Recent applications of medical ultrasonic echography have made possible to achieve PIV on echographic images of tracer particles dispersed into test fluids, termed ultrasonic imaging velocimetry (UIV) [6]. While UIV provides velocity vector filed with a high spatial resolution, it has a low the temporal resolution. It is because UIP requires to transmit an ultrasonic pulse with time lags between the TDXs to do not occur interferences between ultrasonic waves emitted from different TDXs.

Our research group has been trying to extend a dimension of velocity components obtained from UVP by applying information of the echo intensity provided from UVP. This method uses two types of particles with different diameters. In this paper, smaller particle means particle in the range of diameter from a quarter to a half of the wavelength of ultrasonic wave, while larger particle means particle with the diameter comparable to the wavelength. With the smaller particles, the velocity component parallel to the measurement line is obtained with fine spatial resolution comparable to the wavelength by Doppler velocimetry as well as conventional UVP. The larger particles provide relatively stronger reflection echo intensity in comparison with the smaller particle during passage through a measurement line. In the proposed methodology, additional velocity component is given by tracking the particles using echo intensity information like particle tracking velocimetry (PTV). The velocity information to be provided includes the velocity component perpendicular to the measurement line (Fig. 1(a)). The number of larger particles is limited with relatively small to distinguish the echo intensity from individual larger particles, and thus the velocity information provided by the

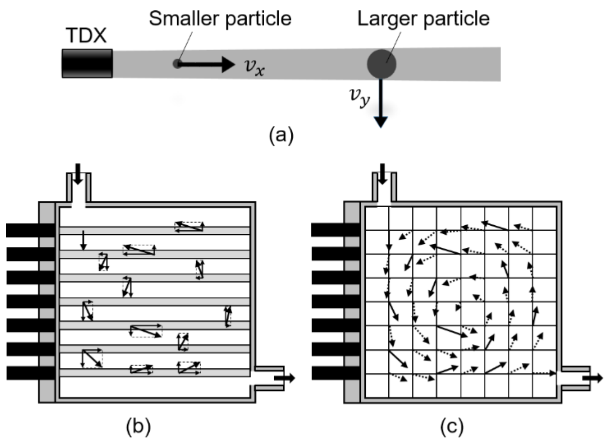

Figure 1: (a) each velocity component obtained from particles with two-difference-diameter; (b) formation derivation of the velocity vectors from Doppler velocimetry and echo intensity method, and (c) processing of interpolation

larger particles is sparse in comparison with the velocity component provided by normal UVP. As a result, dense velocity components parallel to the measurement line and course perpendicular velocity components are obtained on the measurement line (Fig. 1(b)). The information is still insufficient on the combination of them to describe the velocity field. Spatial interpolation on the velocity vector field, which is used for velocity field obtained by PTV, is thus adopted (Fig. 1(c)).

In this paper, as a preliminary step, a relatively simple method to obtain a velocity from time in which the larger particle crosses through an ultrasonic beam is adopted. At first, algorithm to realize the measurement method is established and its applicability is evaluated. Then, a circulating flow in a thin container, which has been often used as benchmark tests for PIV, is measured using the present methodology to evaluate, especially, how the interpolation works to represent velocity fields.

2. Experimental setup

Fig. 2 shows dimensions of the test container, 120 mm × 120 mm × 15 mm, and arrangement of the TDXs for the circulating flows. The container is made of acrylic resin and has an inlet and an outlet; these are connected to a pump for circulation of tap water as the test fluid. By adjusting flow rate from the pump, steady, quasi-two-dimensional circulating flow, which is suitable for evaluation of the present methodology, is formed. For comparison of the measured velocity field, PIV is also adopted; a high-speed video camera was set above the container, and the flow field was illuminated by a green laser sheet at the half height of the container.

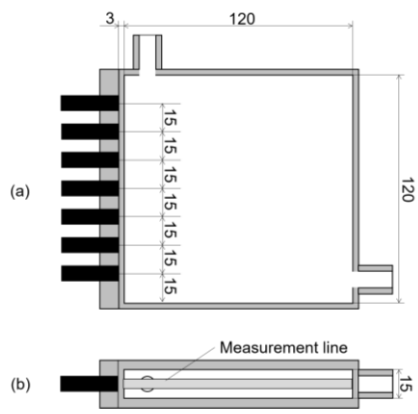

Figure 2: Illustration of experimental container; (a) top view of the vessel and locations of transducers, and (b) side view and UVP measurement line.

Seven TDXs are embedded in the left side wall of the container with equally spacing, 15 mm, and central position of TDX at the end of array places 15 mm from the side wall (Fig. 2). The basic frequency and effective diameter of the TDX are 4 MHz and 5 mm, respectively. The measurement line passes through the half height of the container. Porous resin particles, HP20SS and HP20 (Mitsubishi chemical Co.), were used as "smaller" and "larger" ultrasonic reflection particles. HP20SS has 63-153 µm in diameter and 1.01 in specific gravity. HP20 has 300-700 µm in diameter and 1.01 in specific gravity. For generating ultrasonic waves and signal processing for UVP, UVP monitor model Duo (Met-Flow S.A.) was adopted. Table1 specifies main parameters of present UVP measurement. Because of steadiness of the test flow field, Measurement by each TDX was performed sequentially.

Table 1: Setting parameters of UVP

Base frequency	4.0	MHz
Temporal resolution	4.0	ms
Spatial resolution	0.74	mm
Velocity resolution	3.551	mm/s
Number of cycles	4	-
Number of repetitions	8	-

3. Data processing

3.1 Measurement using echo intensity

In this section, method to measure the velocity component perpendicular to the measurement line using echo intensity information from individual larger particles is explained. As shown in Fig. 1, UVP can measure the velocity component parallel to the measurement line along the line with certain spatial resolution, 0.74 mm in the present setting. Thus, a single TDX obtain two-different velocity components to form 2D velocity vectors.

Because two-different-diameters particles are suspended in the same flow field, it is necessary to distinguish echo information from individual larger particles using magnitude of echo intensity. Both particles used here provide Mie scattering against incident ultrasonic waves and echo intensity from the particle depends on its size. Fig. 3 shows echo intensity with time elapse in the same setting parameter of UVP. The horizontal axis is the time and vertical axis is echo intensity. Fig. 3(a) is echo intensity from HP20SS (smaller particle), while Fig. 3(b) is for that from mixture of HP20SS and HP20 (larger particle) with small amount. There are two different levels of echo intensities that should be provided by the smaller and larger particles in Fig. 3(b). This large variation on the time trace is caused by passage of the larger particles. In this study, perpendicular velocity component is obtained from time in which a larger particle passes through a

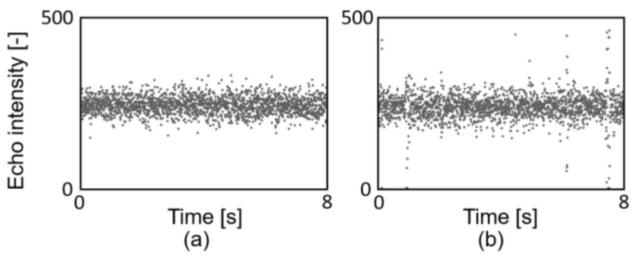

Figure 3: Time traces of echo intensity for (a) only smaller particles, and (b) smaller and larger particles

measurement line, and thus it is necessary to detect only echo variations caused by passage of the larger particles on noisy echo distributions with smaller and larger particles.

To extract the echo information from only the larger particles, filter processing is performed. Laplacian filter is used to emphasize echo variations corresponding to passages of the larger particles. Fig. 4(a) shows original data, while Fig. 4(b) shows data with processing Laplacian filtering. After the filtering, echo variations corresponding to motions of smaller particles are removed by giving a threshold value determined by standard deviation (Fig. 4(c)). On the echo distribution after the filtering processes, a traveling time of a larger particle passing through the measurement line, Δt, is determined by counting a part of remaining echo intensity (Fig. 4(d)). The velocity component perpendicular to the measurement line, v_y, is thus calculated as

$$v_y = \frac{D_\mathrm{u} + D_\mathrm{p}}{\Delta t},$$

where D_u and D_p are diameters of ultrasonic beam and the larger particle, respectively.

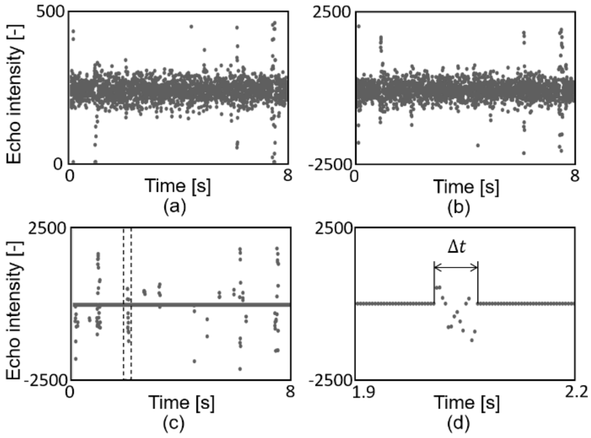

Figure 4: Time traces of echo intensity; (a) raw data, (b) processing Laplacian filter, (c) elimination of small intensities by thresholding, and (d) enlarged view at a part of strong echo intensity scattered by a larger particle

3.2 Validation

A preliminary experiment for validation of the present methodology was conducted by evaluating velocity obtained from echo intensity method. Larger particles were settled in an acrylic pipe filled with water. Porous resin particles, PK216 (Mitsubishi chemical Co.), were used as ultrasonic reflection particles. The particle has 400 μm in median diameter and 1.29 in specific gravity. The acrylic pipe with 1000 mm long and 52 mm inner diameter was used as the test pipe. The expected Reynolds number is around 12 and the flow is not in Stokes regime. For obtaining echo intensity distributions, an ultrasonic transducer with 4 MHz basic frequency was mounted perpendicular to the pipe wall, and the measurement line was set at the center line of pipe. The particles were settled in test pipe under hydrostatic pressure. The sedimentation velocity of particle was measured by the present method mentioned in the last section and compared to the result of PTV, which performed simultaneously. Fig. 5 shows probability density distribution of velocity measured by the present method and PTV. Based on both measurement range, the sampling number of both is different. Averaged velocity from echo intensity method is 33.3 mm/s (Fig. 5(a)), while that from PTV is 31.8 mm/s (Fig. 5(b)). With considering that the velocity measured by PTV contains that from particles passing out of the measurement line of ultrasonic echo intensity, this difference on the probability density function is in quite reasonable range. We therefore conclude that the present velocimetry using echo intensity method works well.

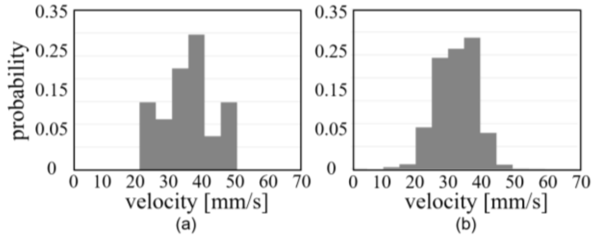

Figure 5: Probability density distribution of the sedimentation velocity from (a) echo intensity method, and (b) PTV

3.3 Interpolation

The dense velocity components parallel to the measurement line by Doppler velocimetry, and the course perpendicular velocity components by echo intensity method are obtained on the measurement lines. At some points on the measurement lines, a velocity vector is formed from these two velocity components (see Fig. 6(a) as an example). At the other points, however, there are only the parallel velocity components. We can imagine flow filed in the container using only few velocity vectors shown in Fig. 6(a) because this experimental set-up is very simple system, but they will be insufficient for more complex system to be understood. That is a similar situation for measurements by PTV; velocity vectors are given at some dispersed points on flow fields. Our research group has often used 2D linear interpolation on dispersed velocity vectors to form regularly arranged velocity vector fields, termed Laplace equation rearrangement (LER) [7]. The Laplace equation in a 2D coordinate system is given as

$$\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} = 0.$$

Lacking velocity vectors (also components) are interpolated to satisfy the equation and boundary conditions by iteration calculations. Lattice point of the flow field to demonstrate LER is set with spatial resolution of UVP data, 0.74 mm as the lattice distance. The iteration calculation was performed with boundary conditions, constant inflow and outflow with averaged flow velocity at the inlet and outlet, slip boundary conditions for other parts, until a convergence condition was satisfied. In the calculation, the original velocity components obtained by

Doppler velocimetry and echo intensity method are not modified.

Interpolations by LER do not guarantee that estimated velocity vector fields satisfy equation of continuity. As an additional process, in cases that quasi-2D velocity fields can be assumed, postprocessing based on data compensation to satisfy equation of continuity, termed velocity correction potential (VCP) [7], has been performed. VCP corrects estimated velocity field by LER. Equation of continuity for 2D incompressible flows is given as

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0.$$

VCP is also performed by iteration calculations for satisfying the equation above with a convergence condition; here the original velocity data are not conserved unlike LER.
Fig. 6(b) shows a velocity distribution after those processing. LER and VCP are independently processed. VCP also works to correct erroneous velocity vectors originally measured. In the present case, Doppler velocimetry provides higher accuracy than the echo intensity method, and later information may be mainly modified.

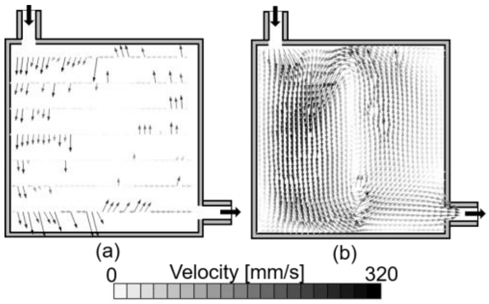

Figure 6: Velocity vectors distribution obtained from (a) Doppler velocimetry and echo intensity method, and (b) after processing LER and VCP

4. Evaluation of estimated velocity field

The velocity vector fields estimated from the present method with LER and VCP, and importance to provide the velocity component perpendicular to the measurement line on the estimation are evaluated. Fig. 7(a) shows a velocity vector field reconstructed by LER and VCP on velocity data with only the component parallel to the measurement line given by Doppler velocimetry, while Fig. 7(b) includes velocity data captured by the echo intensity method. Also, Fig. 7(c) shows a velocity vector field measured by PIV with standard cross-correlation algorithm. Fig. 7(a) does not show the circulating flow exactly. Fig. 7(b) represent faster velocity vectors around the inlet as Fig. 7(c), the PIV result, indicate it, but Fig. 7(a) does not it. Fig. 7(c) shows strong, wider flow along the inlet flow. Fig. 7(b) represents it. Additional information obtained by echo intensity method makes estimations of flow structure more detailed.

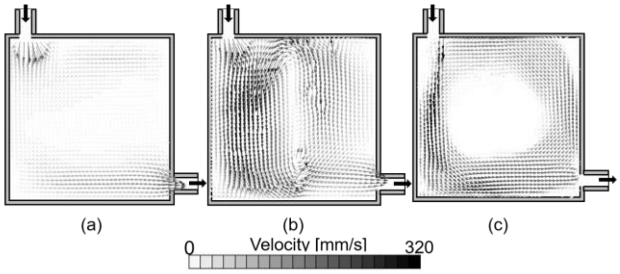

Figure 7: Comparison of velocity vector distributions estimated from (a) velocity data measured by Doppler velocimetry, (b) velocity data measured by Doppler velocimetry and echo intensity method, and (c) corresponding velocity field measured by PIV

5. Sumarry

This study aims to extend a dimension of UVP's measurable velocity components by applying information of the echo intensity with conventional UVP, that provides single velocity component parallel to the measurement line, to capture 2D flow fields. As the initial stage of the development, the velocity component perpendicular to the measurement line is obtained from echo intensity method, where the velocity component is estimated from time of larger particles passing through the measurement line detected by the echo intensity. Velocity vectors, with two components in parallel and perpendicular directions of the measurement line, are thus given at some points on the line. Velocity fields are estimated from dispersed velocity vectors and dense information of the parallel velocity components along the measurement line with interpolation method (LER) and correction method (VCP).A performance test of the present methodology on quasi-2D circulating flow and PIV measurement for comparison indicated that taking additional velocity component perpendicular to the measurement line provides better estimation of the flow field even though the number of data of the velocity component is small.

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