11th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering
Berlin, Germany (5.-7. September 2018)

Flow Monitoring of Particle-laden Flows Combining Ultrasonic Doppler and Echo Intensity Profiling Techniques

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The methodology to reveal inner structures of turbidity currents are required. Their behaviors have important roles to affect the sedimentation or transportation of fine particles. We have proposed a novel monitoring methodology for flows containing fine particles, combing Doppler velocity and echo information obtained from ultrasonic velocity profiler (UVP). In this study, we captured the relationship between the echo profiles and particle number distributions. To simplify turbidity currents, stirring flows in a cylindrical container were chosen. As suspended particles, quartz particles with 13.5 μm in the central diameter was examined. In a certain range of quartz volume fraction α, UVP can detect integral echo signals obeying Rayleigh scattering and Doppler-shift frequencies, although the quartz diameter is much smaller than ordinary tracer particles adopted for UVP. The echo distribution of $\alpha = 1\%$ showed that the stirring flow causes the local particle number distributions. Moreover, the possibility to reconstruct particle number distributions from echo amplitude distributions was indicated.

Keywords: Echo intensity, Particle-laden fluid, Particle number density distribution, Solid-liquid two-phase flow, Rotational flow

1. Introduction

In the hydraulic industry, liquid-solid two-phase flows which contain solid particles have important roles to utilize aquatic resources. For example, collecting minerals and fossil fuels under the sea and transportation or sedimentation mechanisms of solid particles in reservoirs have been paid attention to. An example of them and main topic of our research group is turbidity currents [1-3] which are gravity currents driven by the density difference between particle-laden fluid and ambient fluid. They have complicated flow structures due to turbulence and complex interaction caused between each particle. They show local mixture density fluctuation accompanying clusters and clouds of particles, which is hardly investigated by optical approaches and numerical simulations. Our research group, therefore, has proposed the direct monitoring methodology of such particle-laden flows using ultrasonic technique. Ultrasonic velocity profiler (UVP) [4] can be applied to opaque fluids and measure the spatio-temporal velocity distributions using frequency veering based on Doppler effects. In addition, echo signals which are reflected waves scattered by suspended particles give us beneficial information on particle number distributions. In past studies, scattering processes from clouds of fine particles are researched [5, 6]. Even echo signals obtained from UVP could be used to detect moving interfaces of multi-phase or multi-layer flows [7, 8]. In addition, they were applied to obtain the profiles of suspended sediment concentration [9] and to measure void fractions [10]. Combining two distributions of Doppler velocity and echo information, a novel monitoring methodology for turbidity currents expects to be established.

The objective of this study is to reveal relationship between number density distribution of fine particles and echo information. Stirring flows in a cylindrical container were chosen to simplify particle-laden flows like turbidity currents. As suspension particles, quartz particles with order of 10 μm in the central diameter are examined. This range of particle diameter is less than one-tenth the ultrasonic wavelength of central frequency 4 MHz in water, so Rayleigh scattering, which is almost isotropic scattering, occurs. They are not used for UVP measurement basically, because the intensity of reflected waves from a quartz particle is too small to be detected by ultrasonic transducers. It was, therefore, another objective to elucidate the flow conditions and the volume fractions of the quartz particles that UVP can measure reasonable velocity distributions of particle-laden flows.

2. Experiments

2.1 Experimental setup

The experimental setup is shown in figure 1. The experiments were conducted in a cylindrical container with 100 mm outer diameter, and 3 mm thickness of lateral wall and 120 mm height. The cylinder is made of acrylic resin and filled with test fluids containing the fine particles. The cylinder does not have a lid and thus top of fluid layer is free surface. The cylinder was mounted inside the water jacket to keep uniform temperature and allow transmission of ultrasonic wave from the outside of the cylinder. The flow was driven by a stirrer with 60 rpms in the rotational speed, and a stirring bar dipped into the bottom of the cylinder.

Velocity distribution and echo information were measured by UVP. The obtained ultrasonic signals reflected from clouds of particles were processed by UVP monitor model Duo (Met-Flow S.A.) into spatio-temporal distributions of Doppler velocity and echo information. An ultrasonic transducer with 4 MHz central frequency was fixed in the jacket with a horizontal displacement 10 mm from the center line. This off-axis measurement makes it possible to obtain the velocity component including not only radial but also azimuthal velocity component. In case of rigid body rotation, the obtained velocity components show uniform profile along the measurement line. The advantage of this method, therefore, is that flow structures can be imagined from obtained velocity distributions relatively easily and reconstructed assuming axisymmetric flow field. The transducer was set at 25 mm from the bottom of the cylinder to avoid the blind of ultrasonic propagation due to the free surface. Table 1 summarizes the setting parameters of UVP measurement. Especially, amplification is important parameter in this study. Both values of "gain start" and "gain end" were fixed at constant values not to amplify the echo value depending on the distance from the transducer.

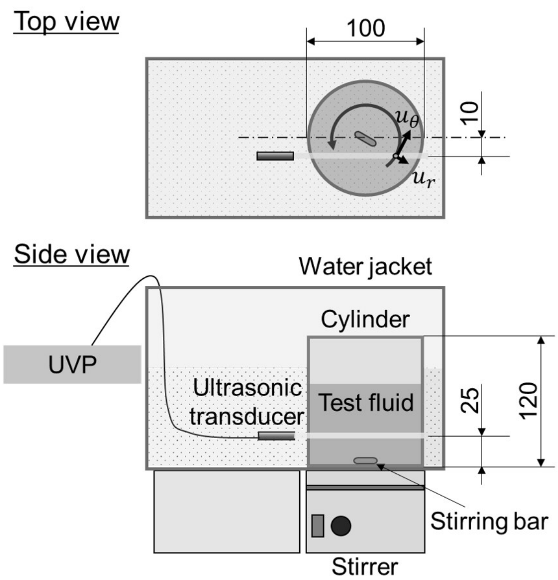

Figure 1: Schematic diagram of experimental setup and arrangement of the measurement line.

2.2 Test fluid

In this study, quartz (Quartz K13, Carlo Bernasconi AG) which is often used as laden particles of experimental turbidity currents was examined. Quartz has particle size distribution and the central diameter is 13.5 μm, and density equals to 2650 kg/m^3. It is predicted that Rayleigh scattering, which is almost isotropic scattering, occurs in the test fluids, because quartz diameter is less than about one-tenth the ultrasonic wavelength of central frequency 4 MHz in water. The cylinder was filled with 500 mL of tap water and quartz was added based on each volume fraction α. Total seven cases with different volume fractions α = 0, 0.01, 0.1, 1, 5, 10, and 15% were conducted.

Table 1: Setting parameters of UVP.

Central frequency	4	MHz
Temporal resolution	10	ms
Spatial resolution	0.74	mm
Velocity resolution	4.75	mm/s
Number of cycles	4	-
Number of repetitions	32	-
Amplification (gain)	6-6	-

3. Results and discussions

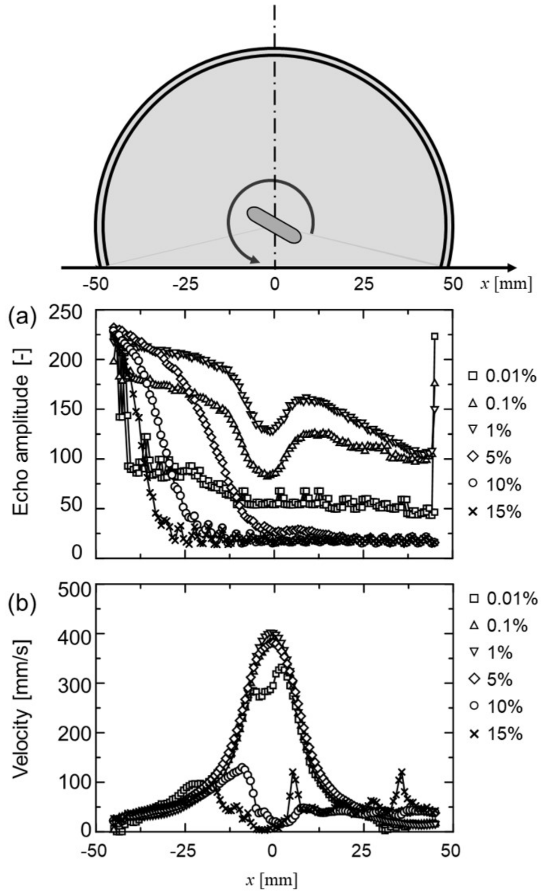

Figure 2: Distributions of time-averaged value of each volume fraction; (a) echo amplitude and (b) Doppler velocity distribution.

Firstly, we tried to comprehend the trends of echo distribution measured in this setup. Figure 2 (a) shows the echo amplitude profiles obtained by UVP in each case. The measurements were conducted for 40 s after the flows reached adequate developed states, and the corresponding number of the velocity profiles for time-averaging is 4000. These echo amplitudes were calculated as the absolute values of difference from background ($\alpha = 0\%$) UVP echo values. In this figure, x axis indicates the distance from the center of the cylinder and the ultrasonic measurement direction is from left to right side. As the volume fraction becomes larger in the cases of $\alpha = 0.01$, 0.1, and 1%, echo amplitude values are getting lager. Their echo amplitudes of these cases show large values on the opposite side from the ultrasonic transducer because of the reflection from the wall. In contrast, the reflected waves from the wall disappears under the conditions $\alpha \geq 5\%$ due to the attenuation of ultrasonic waves and the attenuation is getting larger depending on their volume fractions. Figure 2 (b) shows velocity distributions measured by UVP. These velocities show the components of the measurement direction that contain the azimuthal and radial velocity components. In the cases of $0.1 \leq \alpha \leq 5\%$, reasonable velocity distributions can be observed. In this study, the velocity profiles measured with usual tracer particles (DIAION HP20SS, Mitsubishi Chemical, diameter 60 - 150 µm, density 1020 kg/m^3) is defined as correct distribution, and "reasonable velocity distribution" means having good agreement with the correct distribution. The velocity profiles of $0.1 \leq \alpha \leq 5\%$ have an accuracy that has a high cross-correlation value exceeding 0.95 for the correct distribution. The cases of $\alpha = 10$ and 15%, however, do not show the reasonable velocity distributions. It seems that the attenuation of ultrasonic waves prevents the detection of echo signals by the ultrasonic transducer. In addition, the case of $\alpha = 0.01$ shows a notable result. The velocity values of this case drop irregularly near the center of the cylinder. This phenomenon implies that the amount of quartz particles is much fewer than wall side due to the centrifugal force. As known from the velocity distribution, high velocity values can be observed near the center. As the distance from the center becomes longer, the velocity values are getting smaller. From these distributions, the existence of a free vortex is indicated. The density of quartz is about 2.65 times larger than that of water, so it is possible that particles are blown from the center to near the wall sides by the centrifugal force. These phenomena are indicated by echo distributions too, because their values also drop near the center under the cases of $\alpha = 0.1$ and 1%.

Basically, UVP measurements are applied to flows containing tracer particles with adequate size, density, and concentration to reflect ultrasonic waves. However, the concentrations of particles in these experiments are relatively larger in comparison with the flows of normal UVP measurements. The experimental results for $0.1 \leq \alpha \leq 5\%$ show reasonable velocity distributions. This range of particle concentration, therefore, might be useful to detect integral echo signals obeying Rayleigh scattering. That is why UVP can obtain velocity distribution, although quartz diameter is much smaller than tracer particles.

To reveal the particle number distributions, a supplemental experiment was conducted. The mean volume fraction α was fixed at 1%, because the echo amplitude dramatically dropped near the center comparing to other conditions and reasonable velocity distributions could be obtained. In this experiment, the stirrer worked in the same manner as previous experiments until 20 s. After 20 s later from start of the measurement, the stirrer was turned off. The results of echo amplitude and velocity distributions are shown in figure 3. The velocity distribution shows that the free vortex near the center disappeared immediately after turning the stirrer off. The echo amplitude distribution, moreover, dramatically changes. During the time from 20 to 40 s, homogeneous dispersion of the quartz particles can be assumed, because it had been completely mixed for the first 20 s. During the first 20 s, the low echo region exists near the center. In contrast, that band near the center disappears after 20 s later, and the echo values measured in the far region from the ultrasonic transducer becomes smaller than that of the first 20 s. As the result of this experiment, it is revealed that not only velocity but also echo distribution were changed dramatically depending on the motion of stirrer. It seems that the change of flow velocity induces the local particle number distribution.

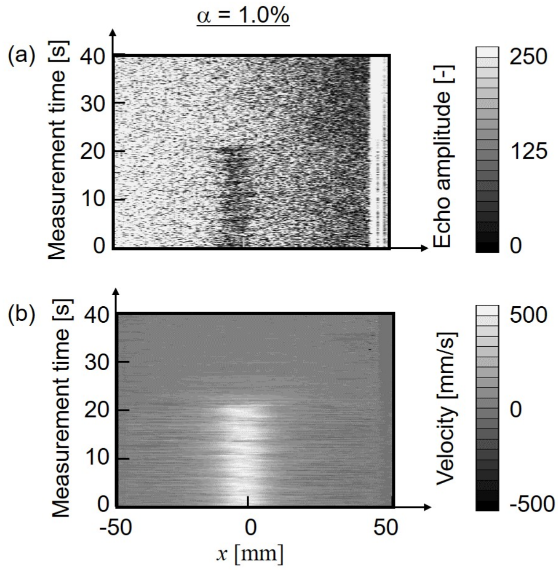

Figure 3: Spatio-temporal distribution of (a) Echo amplitude and (b) Doppler velocity when stirrer was turned off at 20 s later.

To evaluate the relationship between echo amplitude and particle number distribution, time-averaged values of echo amplitude of two cases were calculated. The first is averaged values of the first 15 s and the second is that of the last 15 s. These results are shown in figure 4. The figure 4 shows the characteristic distribution of echo values. The echo values measured in the first 20 s are larger than that of the last 20 s near the both walls, roughly $|x| > 15$. In contrast, the echo values measured in the first 20 s drop sharply near the center. This trend of the echo distribution seems to be related to the particle number distribution. That is to say, the stirring flow causes the free vortex and it blows particles from the center to near the wall sides due to the centrifugal force.

The echo amplitude ratio at two conditions are shown in figure 5 (a). In this graph, the range of x axis shows from 0 to 45 mm which is far side from the ultrasonic transducer. To capture the characteristics of the flow field, Shiratori *et al.* [11] had established the methodology to obtain two velocity components of azimuthal and radial direction assuming axisymmetric flow field. The two velocity components obtained by this methodology are shown in figure 5 (b). In these profiles, the azimuthal velocity is dominant in the cylinder. Range of the lower echo amplitude ratio shown in figure 5 (a), roughly $0 \leq x \leq 15$ mm, corresponds to relatively higher azimuthal velocity range.

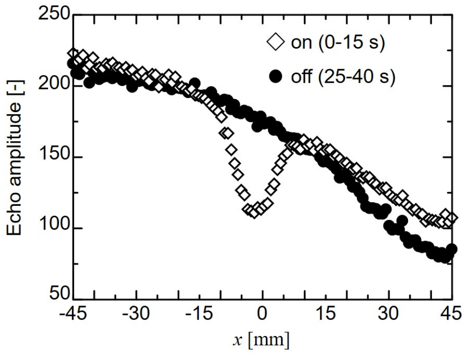

Figure 4: Time-averaged echo amplitude of each case

It would be possible to reconstruct the particle number distributions from echo amplitude ratio. Echo intensity values are the resultant values after some interactions between ultrasonic waves and media including the particles and water, such as attenuation, scattering, and so on. Theoretical models and equations are required to establish the methodology and its applicable range, which can reconstruct particle number distributions.

4. Conclusions

This study revealed the relationship between echo information and number density distribution of fine particles which are much smaller than the wavelength of emitted ultrasonic wave. UVP was applied to particulate rotating flows driven by a stirrer in a cylindrical container. As suspension particles, quartz particles with order of 10 μm in the diameter are examined. Although this range of particle diameter is smaller than ordinary tracer particles adopted for UVP, reasonable velocity distributions could be obtained under the condition where the volume faction of particles α is from 0.1 to 5% due to the detection of the integral echo signals which obeys Rayleigh scattering. Paying attention to the echo distribution observed at α = 1%, the trend of particle number distribution in the cylinder was newly explored. As the result of the experiment, it was confirmed that the range of lower echo amplitude ratio corresponded to the range such that azimuthal velocity is relatively large. It is therefore inferred that the free vortex containing the dominant azimuthal velocity components relates to the local particle number density, which can be predicted from echo amplitude distribution. As the future work, the theoretical models and equations describing the model are required to establish comprehensive methodology to reconstruct particle number distributions from echo values.

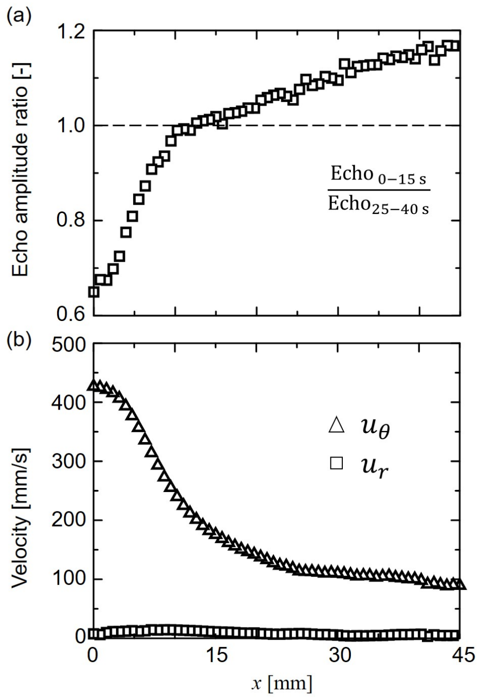

Figure 5: (a) Profiles of echo amplitude ratio at two conditions and (b) profiles of the azimuthal and radial velocity component.

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