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Ultrasonic open channel drainage flow measurement using correlation technique

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ABSTRACT

Conventional ultrasonic flowmeters cannot measue the open chanell unfilled fluid flow. To encounter the problem, a technique was proposed using a single transmitter / receiver transducer attached at the bottom of the pipe. Pulse echo signals scattered from the particles in the medium were repetitively recorded with a constant time interval. From the slope of the correlation peaks with the variation of pulse echo excitation time, flow velocity of the medium was estimated. The method has an advantage that the influence of the water surface variation can be avoided under the condition of the non-turblent laminar flow. To show the feasibility of the technique ,examinations were made for the rippling unfilled water flow in a pipe with diamater 54 mm and length 1000 mm. Flour powder was mixed as scatterers in the imitated drainage water. The flow velocity measured by the present method was compared with that of the predetermined over the range 0-5 cm/s. The results showed that the precision of the measured flow speed was satisfactory and tolerant of the ripping of the water surface in so far as the non-turbulent flow speed was satisfactory and tolerant of the rippling of the water surface in so far as the non-turblent flow conditions were satisfied.

1. INTRODUCTION

With the recent escalation of environmental concerns, monitoring for the flow rates in the flumes and/or drain pipes is much demanded. Conventional ultrasonic flowmeters, such as through transmission travel time method, cannot meet the request. Hence, there are few methods applicable for the unfilled fluid flows in the pipe or small open channel flume[1]. To encounter the problem, a technique[2,3,4] has been investigated based on the observation of the pulse echo signals scattered from the particles in the medium. Special feature of the present technique is that transmit and receive direction is perpendicular to the fluid flow direction and flow velocity is estimated by the correlation calculation between the repetitively excited pulse echo signals. In the present paper, simulation and experiment examinations are made to verify the precision of the flow velocity measurement for the open channel unfilled fluid. To show the feasibility of the technique, examinations were made for the rippling unfilled water flow in a pipe with diamater 54 mm and length 1000 mm. Flour powder was mixed as scatterers in the imitated drainage water. The flow velocity measured by the present method was compared with that of the predetermined over the range 0-5 cm/s. The results showed that the precision of the measured flow speed was satisfactory and tolerant of the ripping of the water surface in so far as the non-turbulent flow speed was satisfactory and tolerant of the rippling of the water surface in so far as the non-turblent flow conditions were satisfied.

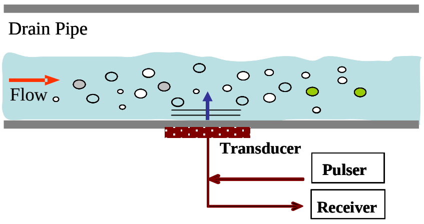


Figure 1. Schematic of the open channel ultrasound flow meter system.

2. PRINCIPLE OF THE FLOW MEASURMENT

As shown in Figure.1, a flow measurement apparatus for the unfilled liquid medium in the pipe is considered, where the medium is flowing with constant speed v in the horizontal x direction. A single transmitter/receiver transducer is attached at the bottom of the pipe. Pulsed waves are repetitively excited at time instant $\tau = nT_{\mathrm{prt}}$ (n=0,1,2...) for every time interval T_{prt}. Echo signals $e(t;\tau)$ scattered from the particles in the flow medium can then be received, where t is the arrival time of the echo signal starting from each excitation time τ. Maximum peak of correlation between the target signal $e(t;\tau)$ and the reference signal $e(t;\tau=0)$ with respect to time t is calculated as

$$R(\tau) = \underset{t'}{\mathrm{Max}} \frac{\int_{t_0}^{t_0+\Delta t} e(t-t';\tau)e(t;\tau=0)dt}{\sqrt{\int e(t;\tau)^2 dt \int e(t;\tau=0)^2 dt}} . \quad (1)$$

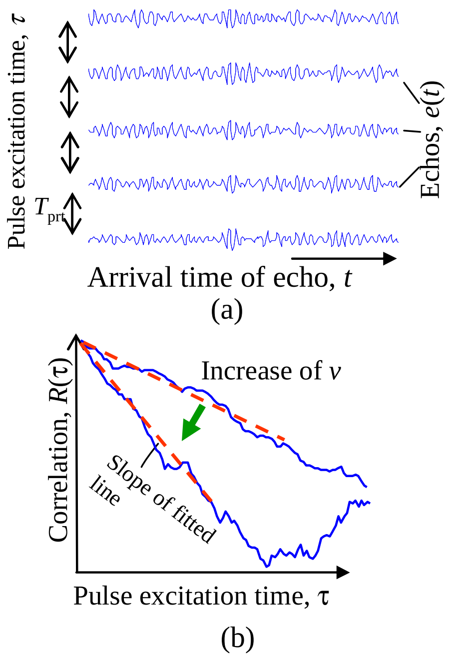


Figure 2. Procedure of flow speed estimation, (a) pulse echo signals, (b) variation of the correlation peak.

Integral range in time is from $t=t_0$ to $t=t_0+\Delta t$. It is related with the water depth as

$$z_0 \sim z_0 + \Delta z = 0.5ct_0 \sim 0.5c(t_0 + \Delta t)\,, \tag{2}$$

where c is sound speed in the water, Δt and Δz are the span of the integration with respect to time t and depth z, respectively.

Suppose that pulse echo signals as shown in Figure 2(a) are repetitively observed. Procedure can then be explained to obtain the flow speed from the observation of the pulse echo signals. Maximum value of the correlation of the echo signals are obtained as shown in Figure 2(b) and its declination slope can be estimated. For the case when the target particles are located at the position within the radiated acoustic beam field in the range $|x|<D_T/2$ (D_T is the diameter of the transducer), $R(\tau)$ takes peak at $\tau=0$ and decreases in proportional to $|x|=|v\tau|$. Furthermore, when the targets go beyond the acoustic beam field in the range $|x|>D_T/2$, the correlation approaches to zero. We note that fluid medium moves a distance $\Delta x=vT_{prt}$ for each pulse excitation time interval. Therefore, the slope of decay ($\Delta R/\Delta\tau|_{\tau=0}$) around the peak ($\tau=0$) is proportional to v (since, $|x|=|v\tau|$). In other words, flow velocity v can be estimated from the slope of the fitted regression line over the correlation curve.

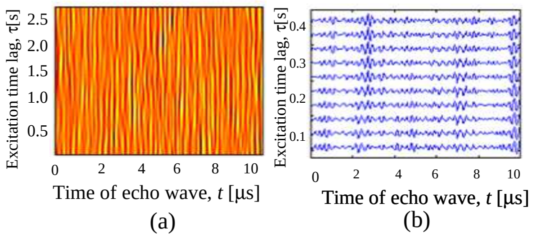


Figure 3. Simulated pulse echo signals for ρ_p=0.2 pcs/mm^3, T_{prt}=10 ms and v=2.0 cm/s. (a) shows the gray scale image, (b) shows amplitude v.s. time plot.

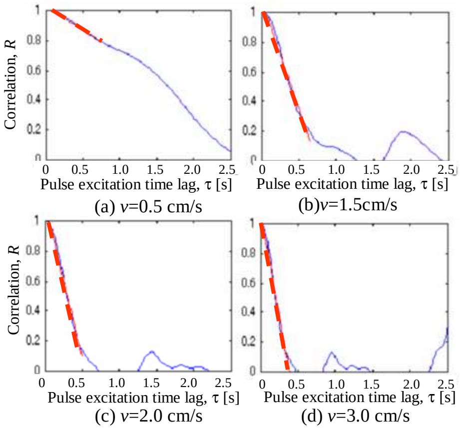


Figure 4. Variation of the correlation as a function of pulse excitation time lag under the condition of T_{prt}=10 ms and different flow speed (a) v=0.5 cm/s, (b)1.5cm/s, (c)2.0cm/s, (d)3.0cm/s. Fitted regression lines are shown with dashed line in the curves.

3. SIMULATION EXAMINATION

3.1 Method

To show the feasibility of the method described above, received echo signals are calculated using the simulation software Field II[5]. In the present simulation, point scatterers with random amplitudes and random locations are placed in the three-dimensional flow pipe space. Transmitted wave field in the flow medium are calculated assuming pulsed wave illumination from the transducer located at the bottom of the pipe. Following, scattered field by the particles and reception amplitude at the receiver aperture are calculated. In the present simulation, flow medium is considered to be the collection of the weak scattering particles. Net echo fields were estimated as the superposition of the impulse response by the individual single particles based on the Born approximation. Parameters are set with same condition in the following experiment. A circular planar disc transducer with diameter D_x=25.4 mm is prepared. Sine pulse wave with frequency f_0=5 MHz and duration 0.5 cycle was emitted from the transducer.

3.2 Synthesis of echo waves

Pulse echo signals with the pulse repetition rate T_{prt}=10 ms are calculated over the excitation time lag τ=0-2.5s (number of excitation N=250). Assuming a constant laminar water flow with speed v=2.0 cm/s, particles in the medium were translated by a distance $\Delta x=v\ T_{prt}$ for each excitation. Calculated echo waves from the particles at the level over the range just below the water surface z=19.5-27 mm are as shown in Figure 3, where (a) shows the gray scale image of the echo amplitude, and (b)shows the plot of the received r.f. echo waveforms. Successive echo waves show close resemblance each other and parallely striped patterns in the grayscale image demonstrate the degree of correlativity between the waves. When the turbulent flows are contained other than the laminar flow, the result exhibits much distorted patterns (effect of the turbulent flow was not considered in the present simulations).

3.3 Evaluation examination of the flow speed measurement

Density of the scattering particles was set with 0.2 pcs/mm^3. The flow speed was changed over the range v=0.5-5.0 cm/s with 0.5 cm/s step. Pulse waves were excited with repetition rate T_{prt}=10 ms. According to the method described in 2, correlation $R(\tau)$ were calculated with the variation of the pulse excitation time τ. The results were shown in Figure 4 with the fitted regression line (red line) at the vicinity of τ=0. We can see the tendency that slope of the regression line increases with the increase of flow velocity v. For the quantitative estimation, slopes of the regression lines were plotted with respect to changing flow velocity as shown in Figure 5. Here, the density of the scattering particles was set with two different cases for 0.2 and 0.4 pcs/mm^3. In order to increase the time resolution, pulse repetition time was adoptively increased according to that of the flow velocity (i.e., T_{prt}=10 ms for v<3 cm/s, T_{prt}=1 ms for v>3 cm/s). It can be seen that the slope of the regression line is in good proportional to the flow velocity and independent of the scattering particle density. Thus, it is expected that the flow velocity can be estimated from the observation of the slope of the correlation curve.

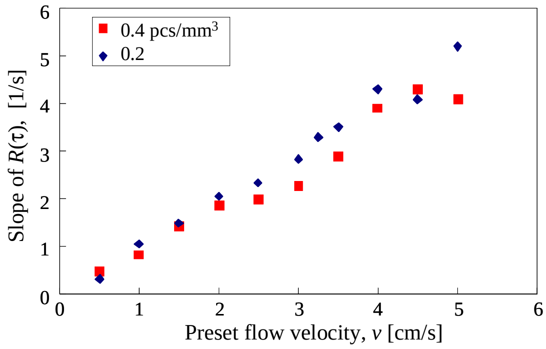


Figure 5. Simulated results of slope of correlation peak as a function of preset flow velocity. Density of the scattering particles is changed as legend parameters.

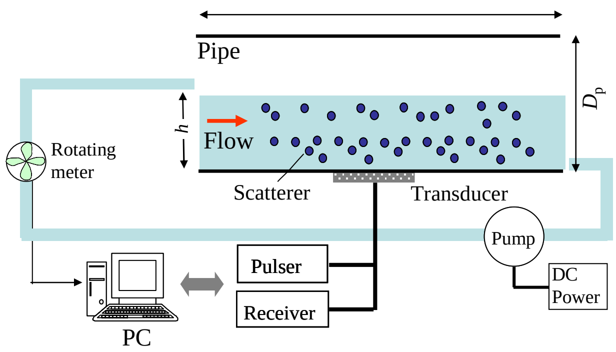
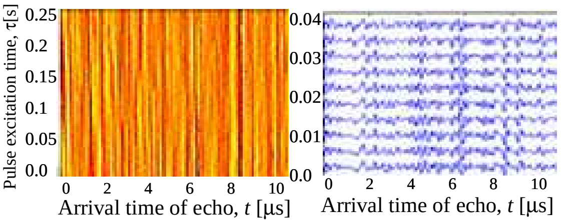


Figure 6. Experimental set-up for the flow velocity measurement.

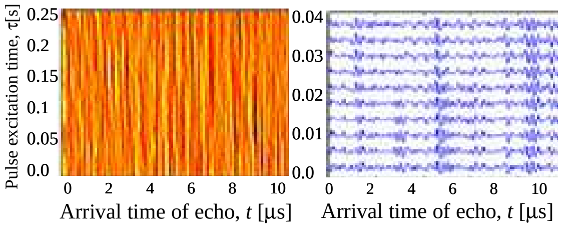
4. EXPERIMENT

4.1 Experiment set-up

Experiment set-up used in the present study is as shown in Figure 6, which was fabricated with the same condition in the simulation. As a drainage mimicking water, flour powder mixed water with density 0.125, 0.25 and 0.5 % was prepared. The solutions were circulated in the horizontally-arranged acrylic pipe with length L=1 m and diameter D_p=54 mm. The flow velocity v was controlled by changing the excitation voltage of the electric pump. Preset value of the flow velocity v was measured by the rotating vane flow meter. A piezoelectric circular transducer with the center frequency f_c=5MHz and diameter D_x=25.4 mm (Panametrics:V307) was attached at the bottom of the pipe. Pulser/receiver (Panametrics: 5058PR) was used for the excitation and amplification of the ultrasonic waves. Finally, they were digitized by the digital oscilloscope and transferred to the personal computer.



(a) v=1.27 cm/s

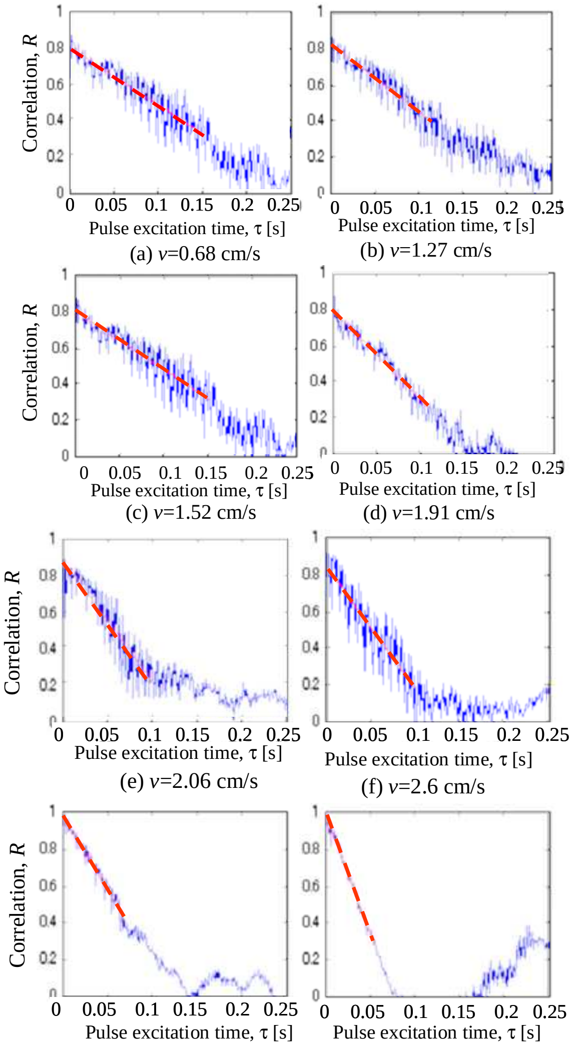


(b) v=4.26 cm/s

Figure 7. Results of observed pulse echo signals for powder density ρ_p=0.5 %, (a)shows the case for preset flow velocity v=1.27 cm/s and (b) for v=4.26 cm/s. Left-hand graphs show the gray scale image, right-hand graphs show amplitude v.s. time plot.

4.2 Experiment result of the flow speed measurement

Flour mixed water was circulated in the pipe. Preset value of the flow velocity v was changed over the range from v=0.68 cm/s to 4.26 cm/s. Pulse echo waves were observed repetitively with repetition T_{prt}=10 ms. Results of observed pulse echo signals for powder density ρ_p=0.5% are shown in Figure 7, where (a) shows the case for preset flow velocity v=1.27 cm/s and (b) for v=4.26 cm/s. It is recognized that the stripe patterns in the gray scale images were slightly violated due to the generation of the turbulent flows. To eliminate the errors caused by the turbulent flows, echo signals were processed dividing the depth range. It is expected that correlativity is maintained in each subdivided segment. With this concept, depth intervals between z=19.5 mm and 27 mm were subdivided with every Δz=0.9 mm spacing, correlation peak $R^{(k)}$ for the k-th depth segment was individually calculated. The correlation peak R was determined from the average of $R^{(k)}$ thus obtained. Figure 8 shows the correlation peak R as a function of the excitation time for different preset flow velocity. Here, fitted regression lines are shown with dashed lines in each graph. As expected, it is confirmed that the correlation peak decays linearly especially at the beginning of the excitation time instant. Finally, the slopes of the fitted lines were estimated for the data obtained for different particle densities. Figure 9 shows the plot of the slopes of the fitted lines as a function of set-up flow velocity v. The results demonstrate that the measured slopes were in good proportion to the preset flow velocity regardless of the density of the powder particles.



(a) v=0.68 cm/s (b) v=1.27 cm/s

(c) v=1.52 cm/s (d) v=1.91 cm/s

(e) v=2.06 cm/s (f) v=2.6 cm/s

(g) v=2.99 cm/s (h) v=4.26 cm/s

Figure 8. Experiment results of the peak correlation coefficients R as a function of pulse excitation time τ for different preset flow velocity v. Fitted regression lines are shown with dashed line in the curve.

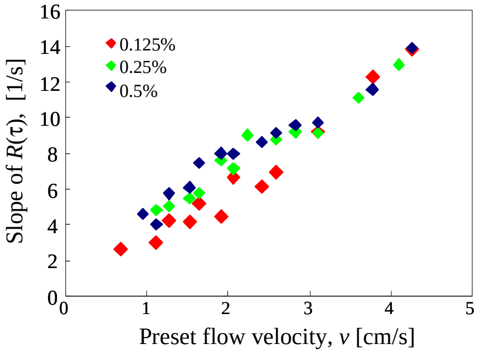


Figure 9. Experiment results of slope of correlation coefficients as a function of preset flow velocity.

5. CONCLUSION

From the results demonstrated above, it was confirmed that the flow velocity can be measured with minimum influence by the variation of flow conditions, which is severely required for the open channel flow. In particular, it is expected that influence of the variation of water level can be avoided if the non-turbulent laminar flow condition is dominant. The authors are proceeding with much elaborate investigations on these points.

6. REFERENCES

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