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Real-Time Ultrasonic Measurement Technique for Monitoring Suspended Sediment Concentration in Reservoirs

Tetsuya Sumi
University of Kyoto, Kyoto, Japan

Yu-Jun Huang, Chia-Chi Sung, Jihn-Sung Lai, Fong-Zuo Lee, Yih-Chi Tan
Hydrotech Research Institute, NTU, Taipei City, Taiwan
adamhuang@ntu.edu.tw

ABSTRACT:
During typhoon flood or rainstorm seasons, rivers usually carry great amount of suspended sediment flowing into reservoir. High concentration of sediment current spread out in all directions in the reservoir, which not only reduces reservoir's life span but also creates treatment problems in the water supply plant. For reservoir operation, real-time monitoring of sediment concentration in the turbidity current has received significant attention from reservoir desiltation operations in Taiwan. Ultrasonic spectroscopy is highly suitable for real-time measurement, in particular for dense particle systems. In the present study, an automatic ultrasonic measurement system is designed and fabricated for measuring solid suspension concentration with respect to the propagation of ultrasound waves in solid-liquid mixture in sites. The measurements obtained by ultrasonic measurement technique for sediment concentration in turbidity currents during 2009 typhoon floods in the reservoir show good agreement with the sampled data. It has been demonstrated that the ultrasonic measurement technique is operative and trustworthy in site with harsh working environments. In the future, the sediment yield in the reservoir watershed may be affected by global climate change in the long term. The ultrasonic device develop has taken the high suspended sediment concentration measurement into account.

Keywords: *sediment concentration, ultrasonic, attenuation, real-time*

1. INTRODUCTION

During typhoon floods or torrential rain seasons, rivers usually carry great amount of suspended sediment flowing into reservoir from its watershed. High concentration of sediment-laden may form a turbidity current in the reservoir, which not only reduces reservoir capacity but also creates water treatment problems for the water supply plant. For instance, it was observed that the sediment concentration sampled near the intake entrance in the Shihmen reservoir, Taiwan, was recorded up to 2.42 x 10^5 ppm during Typhoon Aere (2004). Recent growing interest in sediment concentration monitoring by using ultrasonic diagnostic methods is based on attenuation spectrometry. Sound wave attenuation through dispersed phase suspensions of a continuous second phase material could be used to characterize suspensions. The concentration measuring range of commercial instruments using traditional light scattering methods is usually only up to 30,000 ppm. Ultrasonic methods advantageously penetrate optically opaque mixtures. Spectrometer result errors, caused by particle size, temperature, and trapped air bubbles, strongly affect ultrasonic signals, but can be overcome by good measuring system design. Urick first considered the sound absorption problem in suspensions of one material or another. McClements solved ultrasonic attenuation with a stress-strain relation and equations of state using a boundary condition series expansion at the single particle surface, reviewed by Allegra and Hawley. The Harker and Temple coupled-phase suspension model calculated ultrasonic attenuation in suspensions. All ultrasonic methods intended for liquid flow measurements include several processes: transmission, propagation and reception of ultrasonic waves, signal conditioning, and data processing. During the processes, determining ultrasonic velocity in a movable liquid is the ultimate goal. Relative velocity is mostly measured. Ultrasonic methods can be successfully implemented in a liquid flow measurement because they have satisfactory stability, a wide dynamic range, and allow velocity measurement of electrical conductive and non-conductive liquids both in clean and impure liquids. Although an ultrasonic system has a concentration measurement advantage, it provides only transmitting and receiving signals. In the present study, a novel portable ultrasonic device was designed and manufactured for real-time sediment concentration and flow velocity measurements in the field. A series of experiments were conducted using kaolin and reservoir sediment within a wide range of concentrations up to 300,000 ppm at various temperatures. The experimental data were compared with the numerical results calculated by the coupled-phase model proposed by Harker and Templeto examine the effect of the particle size distribution. Regressed relationships of concentration were also constructed as a function of attenuation and temperature. Through laboratory tests for calibration and validation and had been successfully employed to measure sediment concentration and flow velocity (time-difference method by ultrasonic probes) along water column during typhoon floods in the Shihmen reservoir, Taiwan.

2. THEORY

The coupled-phase model was proposed by Harker and Temple [7] to analyze wave propagation in a two-phase mixture. The model is constructed by four governing differential equations in a system consisting of two continuity equations, Eqs. 1 and 2, the drag on one phase by the other in Eq. 3, and the momentum equation conservation for a solid-liquid mixture in Eq. 4. The model assumes no gravitational field, nor heat or mass transfer between phases. For brevity, we define $\delta = \sqrt{2\eta / \omega\rho_f}$, in which δ is the viscous skin depth, η is viscosity, ω is the angular frequency of the oscillation, and u_f denotes fluid local velocity. In a solid particle suspension, each particle of density ρ_s is assumed to be uniform, spherical, and of radius a.

The continuity equations are written as

$$\frac{\partial}{\partial t}(\varphi\rho_s) + \frac{\partial}{\partial z}(\varphi\rho_s u_s) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}[(1-\varphi)\rho_s] + \frac{\partial}{\partial z}[(1-\varphi)\rho_s u_s] = 0 \tag{2}$$

Equating the sum of related forces to the particle momentum change rate gives

$$\begin{aligned}\frac{\partial}{\partial t}(\varphi\rho_s u_s) + u_s\frac{\partial}{\partial z}(\varphi\rho_s u_s) &= \varphi\rho_f\left(\frac{1+2\varphi}{2(1-\varphi)} + \frac{9\delta}{4a}\right)\frac{du_r}{dt} \\ &+ \frac{9}{4}\rho_f\omega\varphi\left[\frac{\delta}{a} + \frac{\delta^2}{a^2}\right]u_r - \left(\frac{\partial p}{\partial z}\right)\varphi\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{\partial}{\partial t}[(1-\varphi)\rho_f u_f] + u_f\frac{\partial}{\partial z}[(1-\varphi)\rho_f u_f] &= -\varphi\rho_f\left(\frac{1+2\varphi}{2(1-\varphi)} + \frac{9\delta}{4a}\right)\frac{du_r}{dt} \\ &- \frac{9}{4}\rho_f\omega\varphi\left[\frac{\delta}{a} + \frac{\delta^2}{a^2}\right]u_r + \left(\frac{\partial p}{\partial z}\right)(\varphi-1)\end{aligned}$$

(4)

where u_s is the moving particle velocity, ρ_f is the fluid density, and $u_r = u_f - u_s$ denotes relative velocity is the particle volume fraction, and p denotes fluid pressure. We assume variations only in the z direction, and a suspension sufficiently dense to be treated as a volume-averaged continuum.

Equations 1 to 4 can be solved using a wave-like solution. The complex ultrasonic wave number *k* derived is expressed as follows [7]:

$$k^2 = \omega^2[(1-\varphi)\beta_f + \varphi\beta_s]\left\{\frac{\rho_f[\rho_s(1-\varphi+\varphi S) + \rho_f S(1-\varphi)]}{\rho_s(1-\varphi)^2 + \rho_f[S + \varphi(1-\varphi)]}\right\}$$

(5)

Where f is fluid phase compressibility, and β_s is solid phase compressibility. *S* is a complex quantity given by

$$S = \frac{1}{2}\left(\frac{1+2\varphi}{1-\varphi}\right) + \frac{9\delta}{4a} + i\frac{9}{4}\left(\frac{\delta}{a} + \frac{\delta^2}{a^2}\right) \tag{6}$$

Once the complex wave number k is obtained, attenuation α and velocity c can be calculated from $k = \frac{\omega}{c} + i\alpha$.

Apparently, attenuation depends on the particle volume fraction φ, the fluid viscosity η, the particle radius a and the frequency ω. The coupled-phase model in Eqs. 1 to 4 is idealized in a form containing only particles of a single size in the solid-liquid mixture. Experimental verification of this theory requires monodisperse sediments that are difficult to use commercial products in preparation processes. Additionally, sediments sampled from the field contain naturally varying sizes of particles. Therefore, it is necessary to extend the applicability of this model by taking the distribution of particle sizes into account. Thus, attenuation for sediments with various particle sizes obtained by the laser size analyzer (Mastersizer 2000, Malvern Instruments Limited, UK) is approximated by dividing equally the size distribution into i fractions, and obtaining its corresponding percentage of weight from the distribution curve. The resulting attenuation with various particle sizes is expressed as

$$\alpha = \sum_i \alpha_i Z_i \qquad (7)$$

where index *i* denotes the set of particle radius by the size analyzer, αi is the attenuation of set *i*, and *Zi* is the weight percentage of set *i*. The weight percentage for *i* set is defined as

$$Z_i = \frac{m_i}{W} \qquad (8)$$

where *mi* is the particle weight of set *i*, and *W* is the total weight of the mixture. The particle weight and volume of set *i* are written, respectively, as

$$m_i = \frac{4}{3}\pi a_i^3 \rho_s n_i \; ; \quad v_i = \frac{m_i}{\rho_s} = \frac{4}{3}\pi a_i^3 n_i \qquad (9)$$

where a_i is the size of set *i*, and ni is the particle numbers of set *i*. Finally, we obtain the modified expression for attenuation as follows.

$$\alpha = \sum_i \alpha_i \frac{n_i}{N} = \sum_i \frac{3\alpha_i W m_i}{4\pi N a_i^3 \rho_s} \qquad (10)$$

where N is the total number of particles in the solid suspension.

3. MEASUREMENT SYSTEMS AND EXPERIMENTS

Two measurement systems, a model-typed device and a portable ultrasonic device (PUD), are introduced in this section. The model-typed device designed for concentration measurement in the laboratory, while the PUD is a prototype designed for measuring both concentration and velocity in the field. For measuring concentration, both of them have the same designed system keeping the same distance between probes.

The model-typed device is designed for real-time measurement of solid suspension concentration in the laboratory. Figure 1 illustrates the main parts of a standard piezoelectric transducer for generating longitudinal ultrasound. When it is being used as a transmitter, a suitably varying voltage causes the piezoelectric disc to behave as a piston radiator and generate a sound wave in the ‘load’, i.e., the medium in the front of the face of the transducer. The model-typed device is basically used for calibrating the temperature and pressure sensor, estimating the effect of air bubbles, regulating the speed of the stirring machine, testing the performance of the piezoelectric transducer, and obtaining the regression function for specific sediments in the laboratory. With a probe holder keeping the distance of 0.16m between probes, the model-typed device shown in Fig. 3 is calibrated by using various concentration samples to obtain the regression functions for different sediments. The operating concentration range is from 1,000 to 300,000 ppm with resolution of 200 ppm. Measurement accuracy is ±2% and ±5% at concentration ranges less than 50,000 ppm and greater than 50,000 ppm, respectively.

The prototype device, was designed and manufactured for real-time monitoring of solid suspension concentration and flow velocity in the field. All the electronic circuits and transducers in the portable ultrasonic device have the same elements as those in the model-typed device. As shown in Fig. 3, the PUD is 0.75 m in length and 0.25 m in diameter with two pairs of probes. The distances between probes are 0.16 m (i.e. same as that of the model-typed device) and 0.46m for concentration and flow velocity measurements, respectively. The flow velocity measurement range is ±3 m/sec with a resolution of 0.01 m/sec, and its accuracy is ±0.01 m/sec and ±2% for velocity ranges < 0.5 m/sec and 0.5 ~ 3 m/sec, respectively.

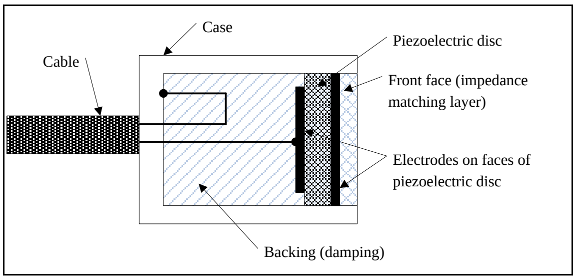

Figure 1. The design of a standard probe.

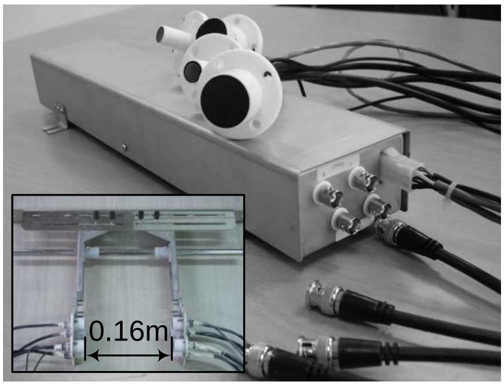

Figure 2. The model-typed device and its probe holder for concentration measurement in the laboratory.

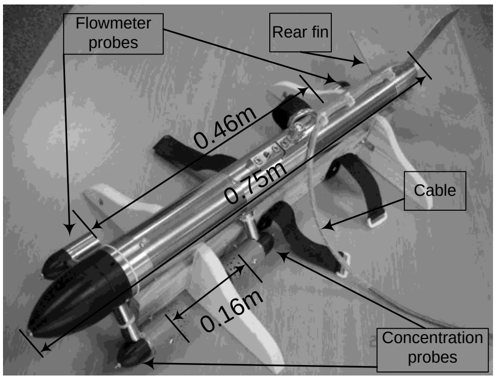

Figure 3. The PUD for both concentration and flow velocity measurements in the field.

The layout of the experimental setup is shown in Fig. 4. The central frequency of probe was 1MHz, and the distance between transmitter and receiver was 0.16m. The experiments were conducted in a 0.6 m long, 0.5 m wide and 0.5 m tall plexiglas cell equipped with two variable-speed mechanical stirrers to maintain a homogeneous particle suspension in the liquid. A four-blade propeller (45° pitch) of 0.2 m diameter provided agitation and was placed at 0.05 m above the cell bottom. The stirrer rotation rate was operated from 500 to 1000 rpm to ensure well-mixed suspension without deposition. It was found that there was no difference in attenuation measurement by operating the stirrer at various speeds, and this was also reported by James and Richard (1999). The temperature was decreased from ambient to 15^{o}C (the lowest temperature recorded during typhoon floods in the Shihmen reservoir) by circulating Freon through a coil installed near the cell bottom. A 1 MHz and 30-cycle tone burst was generated as an ultrasonic signal. The energy loss between transmitter and receiver was measured to obtain ultrasonic attenuation.

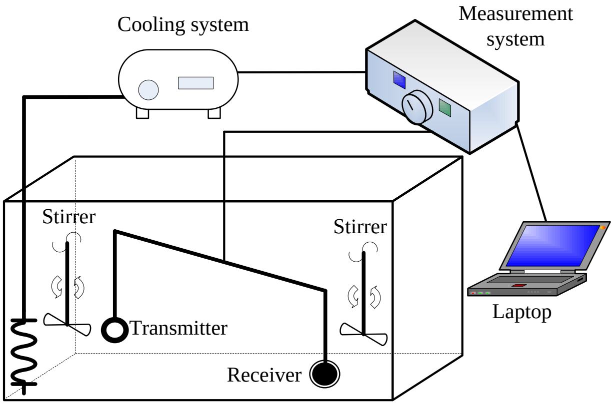

Figure 4. Experimental setup

4. SELF-CONFIRMATION TESTS FOR MEASUREMENT SYSTEM

The entire components of measuring concentration in the PUD are the same as there in the model-type device, except the packing. In order to verify the accuracy of concentration measurements by adopting the regression function in the PUD, a circular tank with a high power stirrer was set up. Figure 5 shows the experimental configuration and the sampling positions in the tank. The PUD was placed at the location between pt. A2 and pt. B2 during experiment.

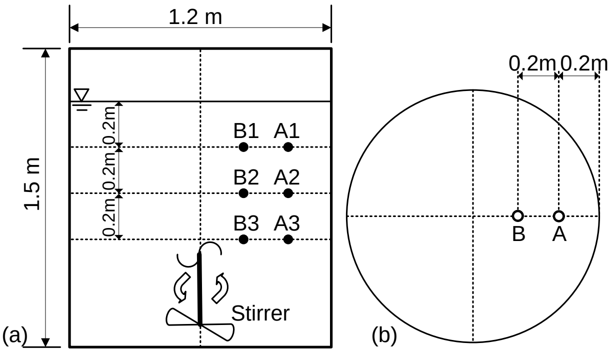

Figure 5. Configuration of the circular tank and sampling positions seen as (a) side view (b) top view

Table 1 shows the results of concentration measurement by PUD in the circular tank, compared with sampling results after extraction and oven drying. For each run, the data obtained from different sampling positions by extraction using a siphon were very close. It indicates that the solution was well-mixed in the tank. The averaged error between measurement and extraction results was 5%, which would be attributable to the system error and could be offset.

Table 1. Concentration measurements by PUD compared with those of extraction samples at 25 °C

Run No.	Sampling Position	Extraction samples (ppm)	Measurement by PUD (ppm)	Error
1	A1	10054	9515	5.4%
	A2	10070		5.5%
	A3	10063		5.4%
	B1	10061		5.4%
	B2	10088		5.7%
	B3	10044		5.3%
2	A1	54353	51907	4.5%
	A2	54327		4.5%
	A3	54310		4.4%
	B1	54367		4.5%
	B2	54295		4.4%
	B3	54245		4.3%
3	A1	99735	95620	4.1%
	A2	99785		4.2%
	A3	99573		4.0%
	B1	99773		4.2%
	B2	99640		4.0%
	B3	99792		4.2%
4	A1	200467	191049	4.7%
	A2	199369		4.2%
	A3	199445		4.2%
	B1	199685		4.3%
	B2	199380		4.2%
	B3	200282		4.6%

Figure 6 shows the photo of the 150 m long, 10 m wide and 6 m deep towing tank with a carriage. In the experiments, the speed of the carriage was controlled as the standard speed and varied from 0 to 3 m/sec in steps of 0.5 m/sec. The PUD was mounted on the carriage and immersed in water, 1 m deep, to measure flow velocity.

Table 2 lists the comparison of flow velocity by PUD and the standard speed by carriage to present very good agreement. The errors in all test runs are less than 2%.

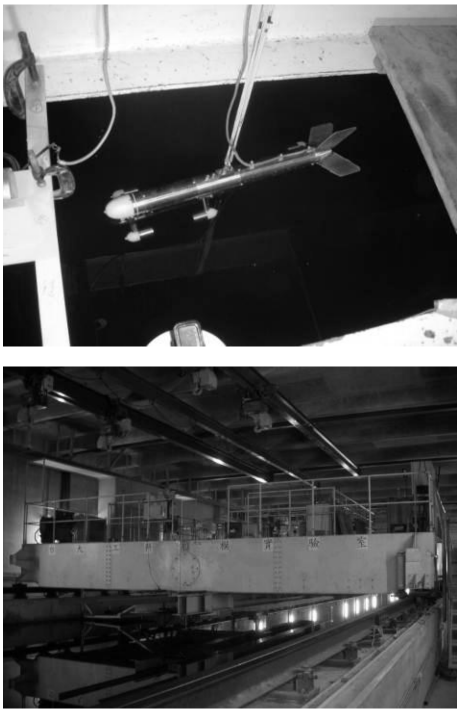

Figure 6. Photo of the (a) PUD mounted on the carriage (b) the towing tank

Table 2. Flow velocity measurements by PUD, compared with standard speeds

Run No.	1	2	3	4	5	6	7
Standard speed (m/sec)	0.00	0.50	1.00	1.50	2.00	2.50	3.00
Measurement (m/sec)	0.00	0.49	1.01	1.50	1.96	2.48	2.97
Error	0.0%	-2.0%	1.0%	0.0%	-2.0%	-0.8%	-1.0%

5. FIELD MEASUREMENT RESULTS

Due to dangerous working conditions, it is usually impossible to conduct measurement on ship during typhoon flood in a reservoir. Fortunately, we had the opportunity to perform real-time field measurements by PUD in the Shihmen reservoir during Typhoon Jangmi on September 30 in 2008, while winds and flows were relatively slow. The Shihmen reservoir is one of the two major multipurpose reservoirs in northern Taiwan, which serves purposes including flood control, water supply, immigration and power generation. Figure 7 shows that the PUD was operated by a motor-driven crane mounted on the ship. The PUD was first lowered into the water and near to the bottom; afterward, the PUD was lifted gradually. As the PUD was continuously lifted up from bottom to surface, the samples of reservoir sediment solutions were collected at several specific positions for validation of the measured data. The sampling time of the PUD was 2 sec to obtain time-averaged concentration and velocity, while the pressure (in terms of depth) and temperature were simultaneously recorded with concentration. The sediment solution samples were taken by a sediment sampler controlled by an electromagnetic valve, and the concentration of each sample was obtained later by oven drying in laboratory.

Figure 7. Operation of PUD in the Shihmen reservoir

The data taken were collected by PUD at Lungchu Bay and the floating barrier, located 4 km and 7 km from the dam, respectively, in the Shihmen reservoir during Typhoon Jangmi. As shown in Fig. 8, the measured sediment concentrations show very good agreement with sampled ones. The vertical profile of sediment concentrations indicates that the turbidity current body (inner region) had about 5 m deep above the bottom and the highest concentration was recorded near the bottom of the reservoir. The flow velocities measured are plotted together with the data taken by a 2D electronic current meter (ACM2-RS, ALEC CO., LTD.). In Fig. 9, the vertical velocity profile of turbidity current has a maximum velocity in its inner region (inside the body of the turbidity current), directed downstream; in the outer region the upstream velocity reflects the backflow of ambient fluid in still reservoir water.

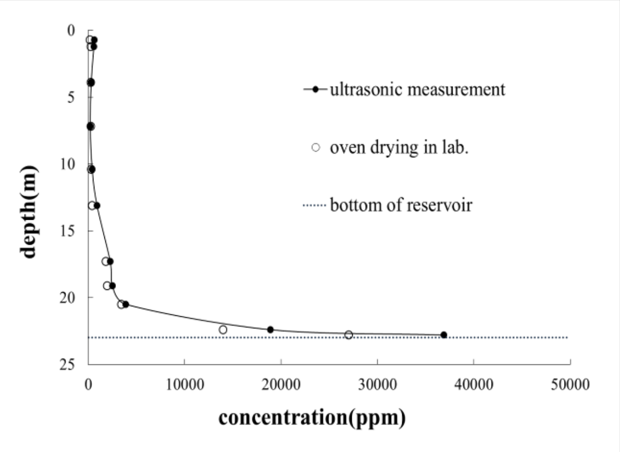

Figure 8. Measured data (2008/9/28/1pm) by PUD and sampled data at the floating barrier in the Shihmen reservoir

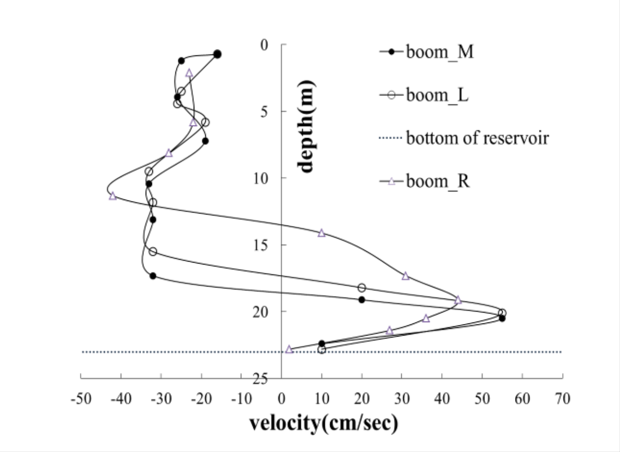

Figure 9. Velocity profile data (2008/9/28/1pm) by PUD at the floating barrier in the Shihmen reservoir

6. CONCLUSIONS

In summary, the modified coupled phase model (ultrasound propagation in particulate mixtures model) is used in this research. The theoretical attenuation by weight percentage has better consistency with experiment results. The particle size radius dominates the attenuation slope, causing a slight difference between prediction results and measurement results. Attenuation for both theoretical results increases with increasing concentration and decreasing particle size.The good experimental results were found by employing PUD for sediment concentration and flow velocity measurements in turbidity currents during Typhoons Sinlaku and Jangmi floods in Shihmen reservoir, which demonstrates that the PUD is operative and trustworthy on site.

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