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# CONTINUOUS MEASUREMENT OF FLUSHING DISCHARGE FROM RESERVOIRS

MASAO IKEDA(1), KIYOSHI KAWANISI(2), MAHDI RAZAZ(2),
KAZUHIKO ISHIKAWA(2) and NORIYUKI MIYAMOTO(1)

1) Keisoku Research Consultant Co Ltd.
665-1, Fukuda1-chome, Higashi-ku, Hiroshima, 732-0029, Japan
2) Civil & Environmental Engineering, Hiroshima University
1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527, Japan

## Abstract

A Fluvial Acoustic Tomography System (FATS) was developed to enable continuous observation of the flow rates of rivers with tidal area, shallow and wide rivers, and flows during floods, which had been difficult with conventional flow rate observation techniques. The ultrasonic waves used in FATS, unlike those in the conventional ultrasonic flow meter AVM (acoustic velocity meter), propagate so as to cover a horizontal cross section, making it possible to obtain the cross-sectional average flow velocity.

The observation site was located in 120 m wide strait reach in the Ghono River, Miyoshi City, western Japan. In order to regrow new sphagnum, the water from the Haizuka and Haji reservoirs is instantly discharged once a year. The flow rates estimated by the FATS which have 25-kHz braodband transducers were compared with those measured by RC and ADCP. Comparing FATS discharge with RC and ADCP discharge, FATS can mesure flow rate accurately under conditions difficult to measure flushing discharge because of high -turbidity.

Keywords: acoustic tomography, flow rate, water temperature, flushing discharge, shallow and wide river flow

## 1. INTRODUCTION

The first purpose of river planning is flood control. River channel plans are established so that flows up to the flow rate (high water level) which is discharged into the river channels of the surrounding river systems due to precipitation are conducted safely downstream. From the viewpoints of proper use of rivers, maintenance of river functions, and environmental protection, securing a normal flow rate is also one purpose of river planning. In these planning processes, flow rates are calculated from runoff analysis based on actual past records of precipitation and water demand. However, reliable river flow rate data are essential for verification of the appropriateness of the analytical model and parameters and for improvement of the analytical accuracy.

Accordingly, establishment of a technology which enables continuous, accurate measurement of river flow rates is an urgent issue. In flow rate measurements with the conventional techniques of float measurement, ADCP, and propeller type flow velocity meters, only temporary flow rate measurements are possible. Moreover, with the conventional flow rate observation methods, it was difficult to observe flow rates under conditions such as (1) flows with salt wedge intrusion, as in rivers with tidal area, (2) shallow and wide rivers, and (3) during floods, which cause high turbidity. Therefore, the authors developed a new Fluvial Acoustic Tomography System (hereinafter, FATS) to overcome these weaknesses, and realized automatic continuous flow rate measurement.

In previous work, Kawanisi (one of the authors) et al. succeeded in continuous observation of flow rates in tidal areas and similar environments using FATS, and confirmed that practical river flow rate measurement is possible with FATS. In the present reserch, FATS which have 25-kHz braodband transducers was applied to streamflow measurement at the Ghono River (Ghono-kawa), which is a gravel-bed river that flows through Miyoshi City, Hiroshima Prefecture, Japan, and the applicability of FATS to flushing discharge was verified by comparison with RC and Acoustic Doppler Current Profiler (ADCP).

## 2. MATERIALS AND METHODS

### 2.1 PRINCIPLE OF FATS

The fundamental principle of FATS is similar to that of the acoustic velocity meter (AVM), in that the average cross-sectional flow velocity is calculated based on differences in propagation time. With AVM, the average flow velocity of an acoustic ray traversing straight across the river is measured. Therefore, observation to compensate for AVM is applied (for example, by IVM). Unlike AVM, the ultrasonic waves in FATS are reflected between horizontal cross sections and do not require complex processing. In cases where the flow of a river is unidirectional, the flow rate can be calculated simply by measuring one part of the flow velocity component of the cross section. When there is a flow in the direction of the measurement line between a set of 2 transducers positioned in the water, the flow velocity between the transducers will be different in the ultrasonic waves propagating in the flow direction and in the counter-flow direction, resulting in a difference in the propagation times obtained at the respective transducers. With FATS, the average flow velocity between the transducers is obtained using this difference in propagation time.

Fig.-2.1 shows the geometrical relationship between a pair of FATS transducers installed in a river. The transducers are set up at position A on the upstream side and position B on the downstream side. Reciprocal ultrasonic waves are transmitted simultaneously by the two transducers at 1 minute intervals, and the propagation times of the ultrasonic waves are measured.

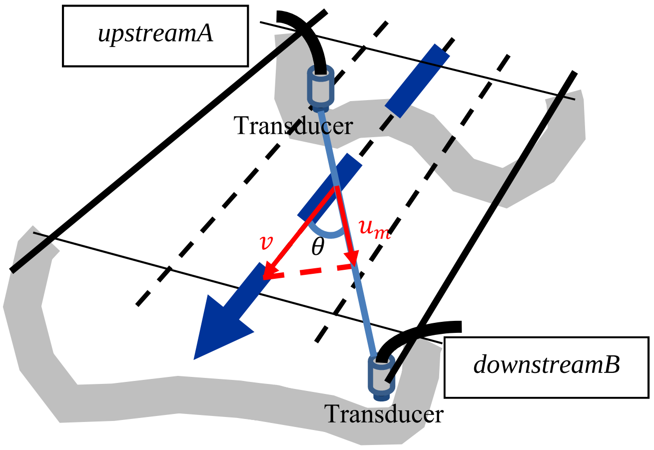

*Fig.-2.1 Installation of transducers in FATS*

Assuming the mean speed of sound obtained and the mean flow velocity along an acoustic ray path of length $L$ are $C_m$ and $u_m$, respectively, the propagation time $t_1$ of an ultrasonic wave propagating from the upstream side to the downstream side and the propagation time $t_2$ of an ultrasonic wave propagating from the downstream side to the upstream side can be expressed as follows.

$$t_1 = \frac{R}{C_m + u_m} \quad (1)$$

$$t_2 = \frac{R}{C_m - u_m} \quad (2)$$

From (1) and (2), the mean speed of sound $C_m$ and the mean flow velocity $u_m$ along the ray path can be obtained from equations (3) and (4).

$$C_m = \frac{L}{2}\left(\frac{1}{t_1} + \frac{\mathbf{1}}{\boldsymbol{t_2}}\right) \approx \frac{\boldsymbol{L}}{\boldsymbol{t_m}} \quad (3)$$

$$u_m = \frac{L}{2}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \approx \frac{{C_m}^2}{2L}\Delta t \quad (4)$$

Where, $t_m = (t_1 + t_2)/2 \approx t_1 \approx t_2$, $\Delta t = t_1 - t_2$

From Eq. (3) and (4), the relative errors of $C_m$ and $u_m$ are given by Eq. (5) and Eq. (6), respectively.

$$\frac{\delta C_m}{C_m} = \frac{\delta L}{L} - \frac{\delta t_m}{t_m} \quad (5)$$

$$\frac{\delta u_m}{u_m} = \frac{\delta L}{L} - 2\frac{\delta t_m}{t_m} + \frac{\delta(\Delta t)}{\Delta t} \quad (6)$$

Because the error of mean propagation time $\delta t_m$ can be ignored if simultaneous signal transmission and receiving can be performed in both directions, the second term on the right side can be eliminated (Kawanisi (one of the authors) et al., 2008). Accordingly, the relative error of the mean speed of sound is equal to the relative error of the distance of the ray path, and time accuracy is not important. On the other hand, because time error, which is the denominator of the third term on the right side of Eq. (5), is small, securing time accuracy becomes extremely important in the relative error of the flow velocity. Normally, the distance accuracy necessary in flow velocity measurements can be sufficiently secured. The speed of sound is a function of water temperature, salinity, and pressure. According to *Medwin* (1975), the speed of sound in water $C$ can be expressed as shown by Eq. (7).

$$\begin{aligned} C = {} & 1449.2 + 4.6T - 0.055T^2 + 2.9 \times 10^{-4}T^3 \\ & + (1.34 - 0.01T)(S - 35) + 0.016D \quad (7) \end{aligned}$$

where, $T$ is water temperature (°C), $S$ is salinity, and $D$ is water depth (m).

The streamflow is calculated as follows.

$$Q = A(H)v_m sin\theta = A(H)u_m tan\theta \quad (8)$$

where, $A(H)$ is the area of the horizontal cross section through which the acoustic ray passes and is a function of the water level $H$.

To measure the mean cross-sectional flow velocity with greater accuracy, ultrasonic waves should be propagated so as to cover the horizontal cross section as completely as possible. A stratification does not exist under shallow waters. Therefore, under this condition, the ultrasonic waves of FATS are propagated so as to approximately cover the horizontal cross section.

In order to determine accurately the arrival time of ultrasonic waves, which contain noise, the M-sequence is used in the transmitted signal, and the transmitted wave is subjected to phase modulation by the M-sequence, which is a pseudo random noise signal. By sending a transmission wave with phase modulation smaller than the frequency band width, SNR is increased in accordance with the relationship ($2^n - 1$), where $n$ is the order of the M-sequence. In this paper, an M-sequence with a order of 10 was used. The M-sequence is also used in the received signal in the same manner was with the transmitted signal, and the mutual correlation between the M-sequence used in the received signal and the transmitted signal is obtained. By accurately measuring the propagation time using a GPS clock, the processing described above can be used to designate the arrival time. As a result, it becomes possible to measure the mean cross-sectional flow velocity and the river flow rate over an extended period of time, even in rivers affected by tides.

## 2.2 STUDY AREA

The river where field observation was carried out was the Ghono River, which flows through Miyoshi City, Hiroshima Prefecture, Japan. Fig.–2.2 shows the observation points on the Ghono River. The observation points were set up 2.7 km downstream from the confluence of the Basen River and the Saijyo River, which are the two main tributaries of the Ghono River. The basin of the Ghono River has an area of 3900 km$^2$. The average annual flow rate at a gauging station 1.1 km downstream from the observation points is 73 m$^3$/s. The Ghono River is a habitat for *ayu* fish (Japanese trout). To stimulate reproduction of the Sphagnum moss that grows on rocks in the river bed and is a source of food for *ayu*, flashing discharge is performed once each year from the Haizuka Dam, which is located on a branch of the Basen River 26 km upstream from the observation points. The river is 115 m in width at the observation points where the transducers were set up to measure the flow rate. The gradient of the river bed between the transducers was 0.11%, and the Manning’s Roughness Coefficient was 0.03. The water depth at low water level was approximately 0.6 m.

The streamflow measurements performed on March 22-23, 2012 were conducted during flushing discharge from the Haizuka and Haji dams, which are located upstream from the observation points, in order to verify the applicability of FATS to periods of flooding. Also preliminary observation was conducted in October, 2011. In Fig.-2.2, T1 and T4 denote broadband transducers of FATS. In order to measure the water depth, which is necessary for obtaining the cross-sectional area of the horizontal cross section, water level gauges were set at the same positions as the transducers on the two river banks.

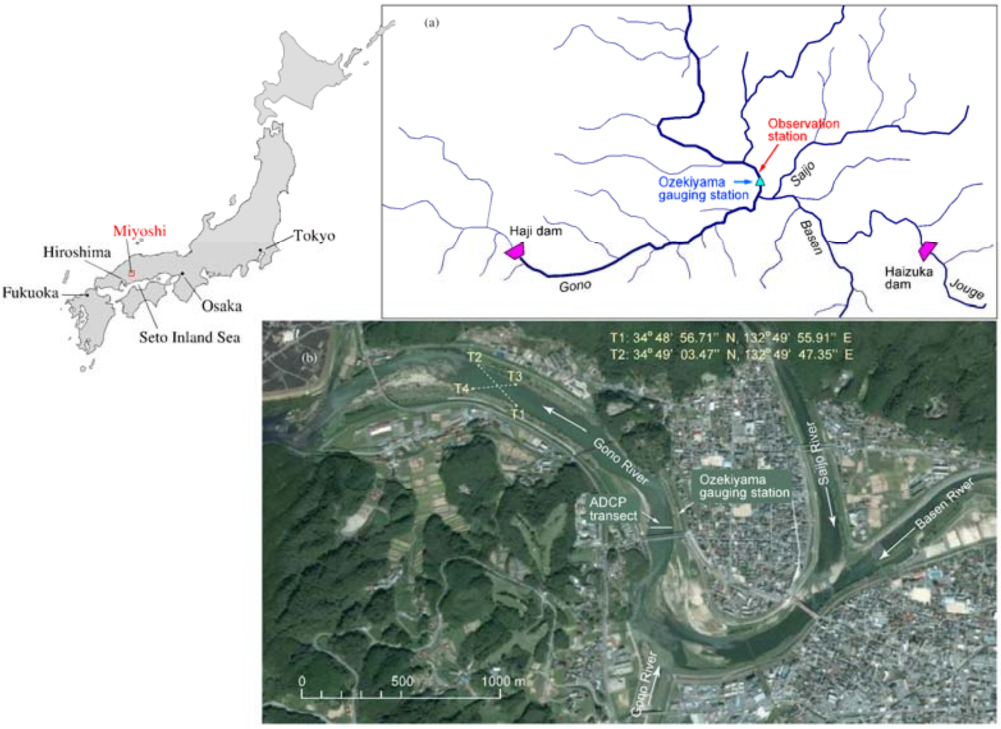

*Fig.–2.2 Location of observation points*

## 3. RESULTS AND DISCUSSION

### 3.1 RESULTS OF CONTINUOUS MEASUREMENT OF FLOW RATE BY FATS

Fig.-3.1 and 3.2 show time plots of the flow rate and water temperature during the observation period in October 2010. In Fig.-3.1, the flow rate measured by FATS is a 30 min moving average. The flow rate by the Rating Curve Methods was obtained from the telemeter water level at 1 hour intervals. In the horizontal cross section between the two transducers, the minimum water depth during this observation period was approximately 30 cm.

The results demonstrated that FATS functions without problems even under this type of shallow water depth condition. In Fig.-3.2, the blue, green, and red lines show the water temperature as obtained by FATS, the diver water level meter, and the telemeter water temperature, respectively. Comparing the results of the water temperature measurements by FATS and the diver water level meter, it can be understood that continuous, high accuracy measurement of water temperature is also possible using FATS.

Fig.-3.3 shows the results of flow rate measurements during the flashing discharge conducted on March 22 and 23, 2012. FATS also functioned without problems under the high turbidity condition during flashing discharge. The blue line shows the flow rate as obtained by FATS, and the red and green lines show the flow rates calculated from the Rating Curve Methods and ADCP, respectively. Fig.-3.4 shows a comparison of the results by FATS and the Rating Curve Methods and ADCP. The red points show the comparison of the flow rates given by FATS and the Rating Curve Methods, and the green points show the comparison between FATS and ADCP. The respective correlation coefficients are 0.9901 and 0.9782, demonstrating that FATS also functions without problems under high turbidity condition during flushing discharge.

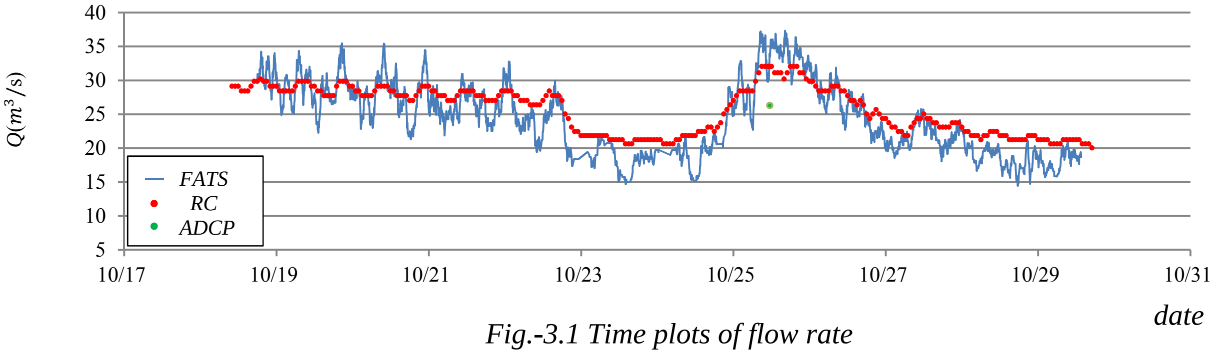

*Fig.-3.1 Time plots of flow rate*

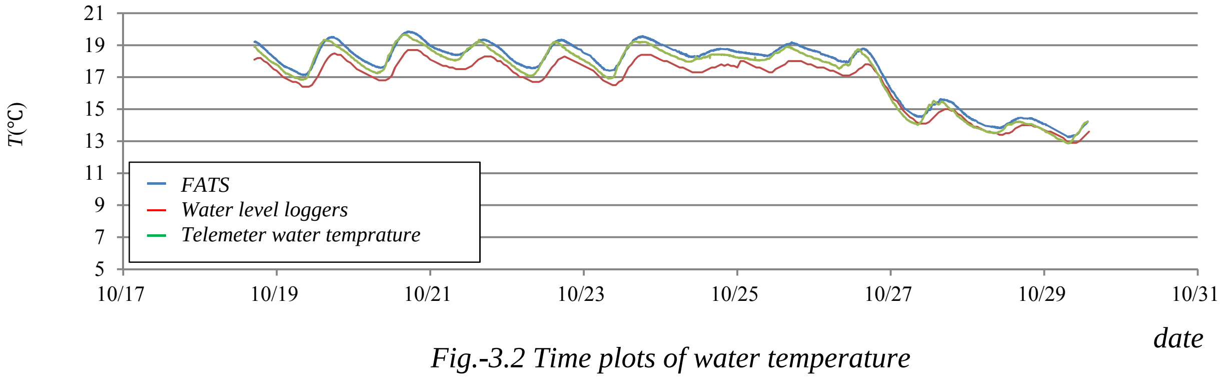

*Fig.-3.2 Time plots of water temperature*

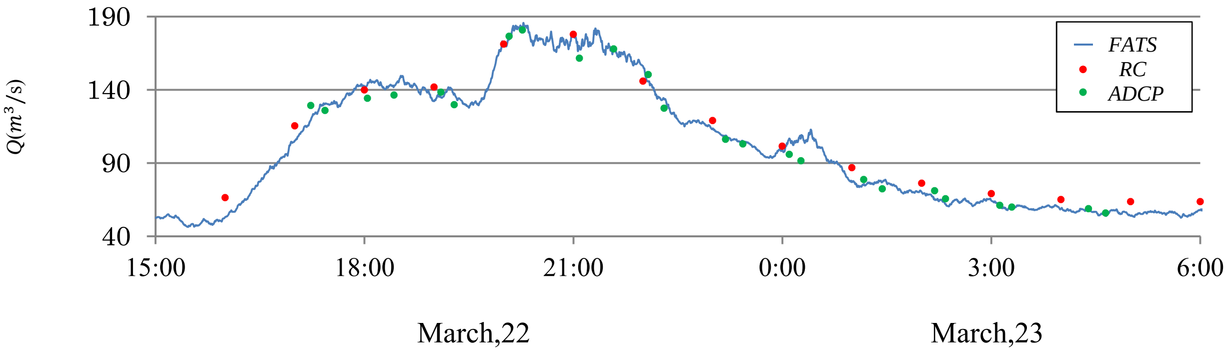

*Fig.-3.3 Time plots of flow rate during flushing discharge*

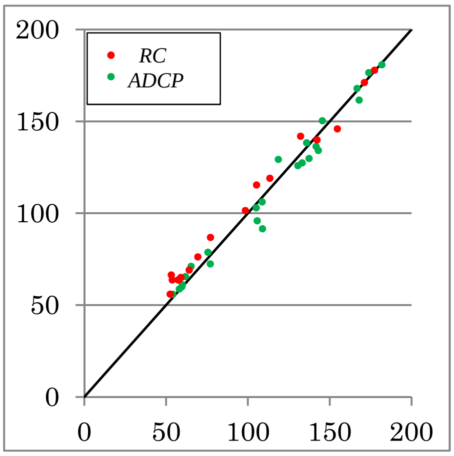

*Fig.-3.4 Comparison of results of flow rate measurements*

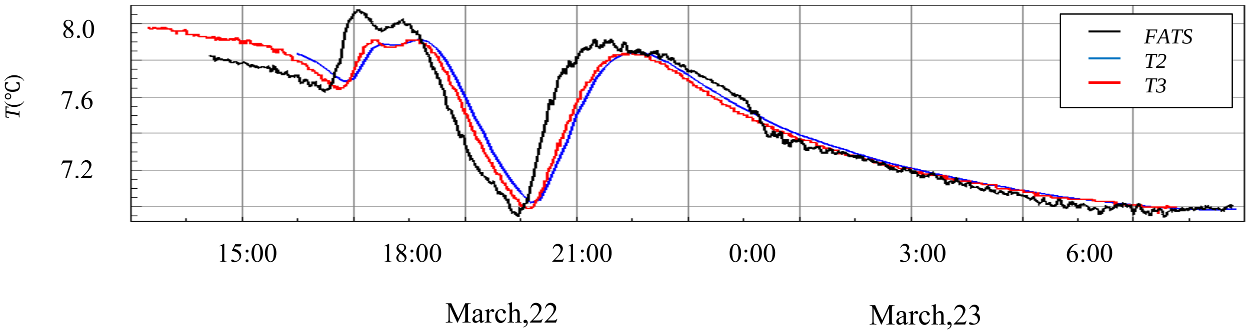

*Fig.-3.5 Time plots of water temperature during the flushing discharge*

Fig.-3.5 shows time plots of the water temperature during the flushing discharge on March 22-23, 2012. The black, blue, and red lines show the water temperature as obtained by FATS, temperature sensors near T2, and T3, respectively. For water temperature from FATS was the cross-sectional average water temperature, the temperature sensors were near the river banks. This may cause the water temperature variation’s time-lag between FATS and thetemperature sensors.

## 4. CONCLUSIONS

The fundamental principle of the Fluvial Acoustic Tomography System (FATS) is based on conventional AVM. However, with FATS, the average cross-sectional flow velocity of rivers can be obtained from ultrasonic waves with a ray path covering the horizontal cross-sectional area.

FATS worked without problems during the observation periods of preliminary observation, in spite of the fact that the water depth at low water stage was approximately 0.6 m and the river width was approximately 115 m. Good agreement was also obtained between FATS and ADCP under high turbidity conditions during flashing discharge (relative error between FATS and ADCP was within ±10%). Thus, these results demonstrated that FATS enables continuous observation of river flow rates at shallow and wide rivers and under high turbidity conditions during flash discharge.

In previous research, Kawanisi (one of the present authors) et al. succeeded in long-term continuous observation of a river with salt wedge intrusion at a diversion channel on the Ohta River in western Japan, and also succeeded in long-term continuous observation of fluctuations in salinity in addition to the river flow rate and water temperature using FATS. These results demonstrate that the advanced acoustic tomography system FATS is a revolutionary device which enables continuous observation of river flow rates of (1) flows with salt wedge intrusion such as tidal rivers, (2) shallow and wide rivers, and (3) flows under conditions of high turbidity during flooding, all of which had been difficult with the conventional Rating Curve Methods, ADCP, and other existing methods.

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