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Ultrasonic Flowmeters for Measuring River Turbulence

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Synopsis

Two kinds of ultrasonic flowmeters have been developed for the precise measurement of turbulent velocity in the stream flow of a river. One is based on the sing-around method, and the other on the method of pulse-time difference. The former especially is able to measure two components of velocity simultaneously. These flowmeters have a number of excellent features: high sensitivity, low inertia, complete linearity, high stability, independence of temperature variation and so forth. The characteristic size of the sensor of both flowmeters is only 3 cm. An adequate combination of the sensors of both flowmeters makes it possible to measure even three components of turbulent velocity simultaneously.

The first half of this paper describes the principle of operation, instrumentation, calibration and several problems to be attended to. In the latter half, the effect of sensor size and the duration of observation on a measured spectrum are discussed. Furthermore, a brief description of observations using the flowmeters is also presented.

1. Introduction

Development of an instrument which is suitable for the precise measurement of the turbulent velocities of river currents has long been required in order to enrich our knowledge of the structure of river turbulence. Various efforts have been made in our laboratory, such as the development of a small propeller-type current meter and hot-film flowmeter. Unfortunately, there was in the past no instrument satisfying the various requirements for turbulence measurement: low inertia, high sensitivity, high stability, high linearity, small dimensions, detection of optional components and so forth. It is a matter of course that the degree of satisfaction of these requirements is determined in relation to the dimentions of the phenomenon and the scale or intensity of turbulence examined.

The stream flow of a river is usually characterized by a large ratio of width B to water depth H. The external scales of river turbulence are supposed to be width B horizontally and depth H vertically. On the other hand, the internal scale is the size of the smallest eddies or Kolmogorov's microscale λ_0. A relatively large differences between these three values seems to suggest that it is expedient to split the range of the spectrum of river turbulence in a wide and uniform channel into two regions: regions $\lambda_0 \sim H$ and $B \sim H$. In the region between λ_0 and H, the turbulence is three dimensional and characterized by the vertical scale H. On the other hand, the turbulence in the region between H and B is quasi-two dimensional and characterized by the horizontal scale B. The former could be called vertical turblence and the latter horizontal turbulence. The double structure of the spectrum has been ascertained by our observation, which show that the length of the largest eddies of vertical turbulence is nearly equal to 10 times the depth of flow and the diameter of the smallest eddies of vertical turbulence is of the order of 10^{-1} cm[1]. Provided that the mean velocity $\bar{u}=10^2$ cm/sec and the depth $H=10^2$ cm, the lower and upper limits of the spectrum of vertical turbulence are about $\bar{u}/10H=10^{-1}$ Hz and $\bar{u}/\lambda_0=10^3$ Hz in frequency, respectively.

From the above considerations, the measurement of the turbulent velocity of horizontal turbulence, which is quasi-two dimensional, large in scale and low in frequency, can be satisfactorily carried out by the usual propeller-type current meter after a little improvement. The measurement of the whole region of vertical turbulence by a single instrument seems to be practically impossible for the time being. A hot-film flowmeter which is considered to be the only instrument which is able to measure the high frequency region of the spectrum cannot operate stably for many hours in a natural river, and furthermore, cannot detect the optional components of velocity without difficulty[2]. An electromagnetic flowmeter which is able to detect the optional components of velocity is used for the measurement of turbulent velocity in a tidal channel[3], but the inertia is not satisfactorily low and the configuration of the sensor does seem not to be suited to our purpose.

From these viewpoints, we intended to apply the ultrasonic flowmeter to the measurement of river turbulence. The ultrasonic flowmeter has recently been demonstrating its ability in the field of atmospheric turbulence. The principle of the ultrasonic flowmeter is based on the fact that in a moving medium the velocity of the propagation of sound is greater in the direction of flow than in the opposite direction. This method has a number of advantages in comparison with other known methods : high sensitivity and accuracy, low inertia, linearity, absence of moving parts, detection of optional components of velocity, independence of temperature variation and so forth. It is at present believed that the ultrasonic flowmeter is the most suitable instrument for measuring the turbulent velocity of river current.

Several kinds of ultrasonic methods have been proposed. The method of pulse-time difference measures the difference of the propagation time of sonic pulse in both the upstream and downstream directions. The method of phase-difference measures the difference of the propagation time in both directions resulting in the difference of phase by use of the continuous sonic wave. The method of frequency-difference measures the difference of frequencies which is a reciprocal of the propagation time. Furthermore, the methods of beam deflection and Doppler shift also exist.

Two kinds of ultrasonic flowmeters with a small size of sensor have been developed for measuring the turbulent velocity of a stream flow. The one is based on the sing-around method, which is a kind of method of frequency-difference and the other the method of pulse-time difference. The former, which especially facilitates the measurement of two components of velocity simultaneously, was developed in 1966[4),5)], and the latter in 1967[6)].

In section 2, the principle of operation, instrumentation and calibration of the ultrasonic flowmeter based on the sing-around method are presented. Those of the pulse-time difference ultrasonic flowmeter are presented in section 3. Several results measured and the method of data processing are presented briefly in section 4.

2. The ultrasonic flowmeter based on the sing-around method

1) *Principle of the sing-around method*

The sing-around method measures the propagation velocity of the ultrasonic pulse in a medium by the use of a pair of transmitting and receiving transducers and a tranceiver which comprises electrical amplifiers and trigger circuit as shown in Fig. 1. The ultrasonic pulse emitted from a transmitter T is received by the receiver R after the time t needed to propagate it between two transducers. The signals received are electrically amplified by the transceiver. The output signals from the transceiver are instanteneously fed to the transmitter to emit the ultrasonic pulse. This electro-acoustic process is continuous. The name 'sing-around' is derived from this. Sonic or electric pulses go round and round as follows: transmitter→medium→receiver→transceiver→transmitter.

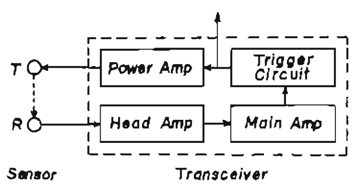

Fig. 1. Principle of the sing-around method. Transmitter T sends acoustic waves to receiver R.

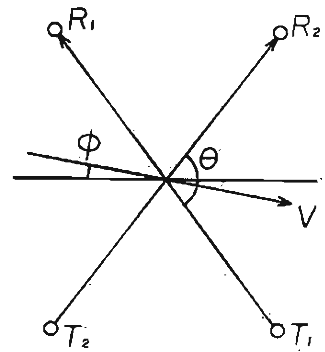

Fig. 2. Two sets of sing-around systems are used to measure axial component of velocity. Transducers T_1 and R_1, or T_2 and R_2 make a pair at intervals of l.

The time required to make a round of the sing-around system is called the sing-around period. The reciprocal of this is called the sing-around frequency. The sing-around frequency in still water is represented by

$$f=\frac{1}{t}=\frac{1}{(l/c)+\tau_e}, \tag{1}$$

where t is the period of sing-around, l the path length, c the velocity of propagation of sound in still water and τ_e the delay time in the electrical circuits. Ordinarily τ_e can be neglected in eq. (1), because

$$\tau_e \ll \frac{l}{c}. \tag{2}$$

In order to measure the velocity of flowing water using the above principle, two sets of sing-around systems must in principle be provided. The arrangement of the transmitters and the receivers of the ultrasonic flowmeter is shown in Fig. 2.

The sing-around frequencies in systems $T_1 \to R_1$ and $T_2 \to R_2$ are, respectively,

$$\left.\begin{aligned} f_1&=\left(\frac{l}{c-V\cos(\theta-\phi)}+\tau_e\right)^{-1},\\ f_2&=\left(\frac{l}{c+V\cos(\theta+\phi)}+\tau_e\right)^{-1}. \end{aligned}\right\} \tag{3}$$

The difference Δf of the frequencies is

$$\Delta f=f_1-f_2=-2Vl\cos\theta\cos\phi\left(\frac{f_0}{c}\right)^2, \tag{4}$$

where f_0 is the sing-around frequency in still water. In the derivation of eq. (4), the condition $(V/c)^2 \ll 1$ is assumed, because c in water is about 1500 m/sec and V less than 10 m/sec. Equation (4) makes it possible to measure the velocity of water from the detection of Δf under the correction of the sound velocity due to the variation of water temperature. The variation of c mostly results from the variation of temperature. Provided that condition (2) is used in eq. (3), a more simple expression of Δf is available instead of eq. (4),

$$\Delta f=-\frac{2V\cos\theta\cos\phi}{l}. \tag{5}$$

In this equation, l and θ are given by configuration of the sensor, $V\cos\phi$ is the velocity component projected to the axis of the sensor. Only the detection of Δf makes it possible to measure the velocity desired. The variation of density or temperature of the water during an observation does not affect the value of velocity measured, because eq. (5) does not contain the term of sound celerity c. The linearity between the velocity and the difference of frequencies is completely ensured. Furthermore, the measurement of the water temperature is possible, because, making f_1+f_2, the velocity term disappears and only term c remains. Therefore, this instrument is very useful for field observations of river turbulence.

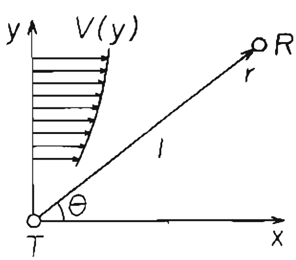

Fig. 3. An existence of the velocity distribution along the acoustic path produces an effect on propagation time of acoustic wave.

Strictly speaking, the expression in eq. (3) is not correct, because the velocity distribution in the region of the sensor is not in general uniform. In the case of the non-uniform distribution of velocity as shown in Fig. 3, the propagation velocity of the sonic wave from the transmitter T to the receiver R is given by

$$t=\int_0^l \frac{dr}{c+V(y)\cos\theta}, \tag{6}$$

where r is the direction from T to R, x the streamwise direction and y the transverse direction to the flow. The assumption that $V(y)=V=$constant in eq. (6) provides the same result as eq. (3).

2) Instrumentation

In order to measure the orthogonal components of velocity simultaneously,

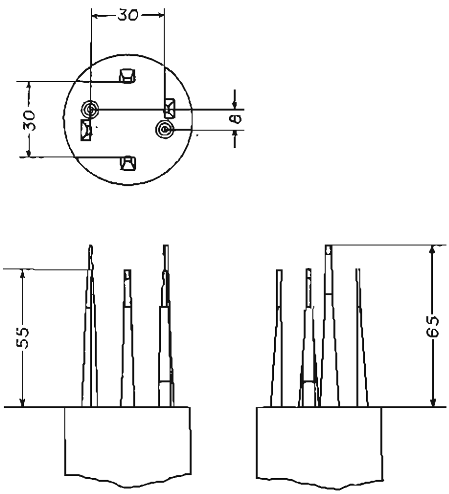

Fig. 4. Practical transducers arrangement of the sensor (mm).

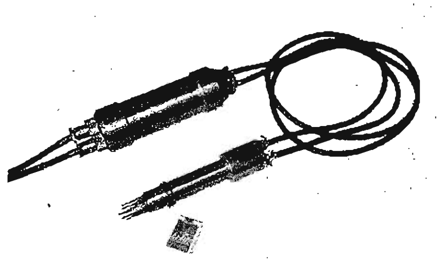

Photo. 1. Probe and detector are connected by a cable 3 m long.

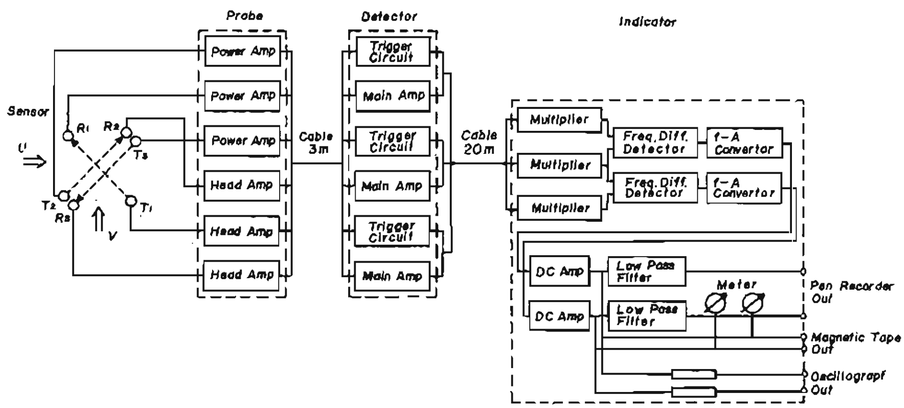

Fig. 5. Simplified block diagram of the sing-around flowmeter.

three sets of sing-around systems should be arranged at least. Such an arrangement of transmitters and receivers is shown in Fig. 4. The angle $\theta=45°$ is adapted in instrumentation to dimish any undesirable influence due to the wakes of the transducers. The sensor of the instrument developed is shown in Photo. 1. The distance between the transmitter and receiver of the instrument is equal to 3 cm.

Figure 5 illustrates a simplified block diagram of the constitution of the ultrasonic flowmeter. The flowmeter consists of three parts: probe, detector and indicator. The sing-around systems mentioned above consist of the probe and the detector, which are housed in water-proofed cylindrical cases of stainless steel and connected to each other by a coaxial cable 3 m long. The probe which has sensors, power amplifiers and head amplifiers is about 35 cm long and 5 cm in diameter. The detector which has trigger circuits and main amplifiers is about 35 cm long and 10 cm in diameter. A barium-titanate element 2 mm×4 mm is used as the oscillation element of the transmitter and receiver. Their dimensions should be sufficiently small in comparison with the acoustic path length to make the distortion of the velocity field due to the wake of the transducers as small as possible. The oscillators are installed at each end of the steel rods 2~4 mm in diameter and about 6 cm in length.

An outline of the action of the instrument is as follows. The electric signal from the detector is, first of all, amplified by the power amplifier as an electric pulse of 40 V amplitude and 10 nanosec duration. This electric pulse is transformed into acoustic energy by the transmitter and emitted into the water towards the receiver. The electric signal received at the receiver is amplified by the head amplifier in the probe and fed to the detector. In the detector, the signal is further amplified by the main amplifier, reshaped in a reshaping circuit to a square wave and fed to a self-running circuit as a synchronizing signal. The synchronized output signal is amplified and transformed into the signal to the transmitter through the low impedance power amplifier. Therefore, sing-around is continued in the circuit of the probe and the detector. In the indicator, three sing-around frequencies led from the detector, f_1, f_2 and f_3, are made 16 times by frequency multipliers, respectively, and the desired differences between them are transformed into electric voltages so as to be indicated on a voltmeter. The indicator also has a set of three output terminals for a magnetic tape recorder, a self-balancing type of pen-writing recorder and an electromagnetic oscillograph.

The main characteristics of the instrument are as follows for each component. The measuring ranges of the velocity are $0\sim\pm4$ m/sec, $0\sim\pm2$ m/sec and $0\sim\pm1$ m/sec, and the output voltage is $0\sim\pm10$ V in each range. The frequency of the ultrasonic pulse is about 10 MHz. The distance between the transmitter and the receiver is 3 cm. The output impedance is less than 600 Ω for a magnetic tape recorder and an electromagnetic oscillograph, and about 10k Ω for a pen-writting recorder. The range of water temperature during operation is 5~25°C. The power source is AC100V, 60 Hz and about 50 VA. The upper limit of the output frequency is 100 Hz for a magnetic tape recorder and an electromagnetic oscillograph, and 0.2 Hz for a pen-writing recorder. The cut-off frequency of the low-pass filters set before the three output terminals is adjustable.

The sing-around method is relatively simple, but there are still various problems in making a stable and accurate measurement. In general, the stability of measurement is influenced by the ratio of signal to noise, that is, the ratio of the amplitude of the propagation signal in the water to the amplitude of the disturbing waves which exist at the same time. It is absurd to increase the power of the propagating signal to the extent that it causes an increases of disturbing waves. One such kind trouble with the ultrasonic flowmeter is the multiplex reflection between a pair of transmitter and receiver. As a countermeasure against this, the beam of the ultrasonic wave emitted from the transmitter is concentrated within an angle of 15° by the use of a spherical lens. This technique also eliminates undesirable influences on the other sing-around system. With measurements very close to a solid wall or the free water surface, the reflection of signal waves from such boundaries disturbs the normal operation of the sing-around system. This kind of trouble, however, is not fatal, because it is easy to find out the error resulting from such a trouble from the record.

The sing-around period contains the fixed delay time which is peculiar to the system, and consists of the delay in the electric circuit, the cable and the coating material of the transducers, and of the delay in triggering due to the transmitting pulse. It is well known that the latter is due to the fact that the wave used in triggering is not the first wave of the transmitting wave. However, the precise determination of the delay is in general very difficult. This is the electric delay time τ_ε presented before, and the electric circuit must be designed as $\tau_\varepsilon \ll (l/c)$. In the instrument presented here, τ_ε is estimated as about 2% of l/c, because $\tau_\varepsilon \approx 0.4\mu$ sec and $l/c = 3/150{,}000 = 20\mu$ sec.

The trespass of additional substances on the acoustic path between the transmitter and the receiver brings about the entire interception of the acoustic beam or the damping of the sonic waves which is liable to change the trigger wave. A slight change of the distance between the transducers exerts a great influence on the value of the velocity measured because of the independence of the three sing-around systems. The sing-around frequencies and their difference are normally,

$$f_1 = \frac{c - V\cos\theta}{l}, \qquad f_2 = \frac{c + V\cos\theta}{l}, \qquad \Delta f = -\frac{2V\cos\theta}{l}, \tag{7}$$

where angle ϕ in Fig. 2 is neglected for simplicity. If the length of one acoustic path changes from l to $l \pm \Delta l$, they become,

$$f_1' = \frac{c - V\cos\theta}{l \pm \Delta l}, \qquad f_2' = \frac{c + V\cos\theta}{l}, \qquad \Delta f' = \frac{-2V\cos\theta \mp c\varepsilon}{l} \tag{8}$$

where $\varepsilon = \Delta l / l \ll 1$. Therefore, the effect of the change of the acoustic path on the sing-around frequency is given by,

$$\frac{\Delta f'}{\Delta f} = 1 \pm \frac{c\varepsilon}{2V\cos\theta} = 1 \pm \frac{\varepsilon}{V} \times 10^5, \tag{9}$$

because $c = 1.5 \times 10^5$ cm/sec and $\theta = 45°$. It is shown from this equation that the change of 1μ in the acoustic path causes that of 3% in the sing-around frequency when the velocity is 100 cm/sec. The major causes of this kind of error are the deformation of the supporting rods of the transducers due to external forces, variation of water temperature or creep of the materials used. Therefore, corrections must occasionally be made by a calibration test.

3) *Calibration*

The calibration of the instrument was carried out in a large-sized ship model towing tank. The instrument was installed on the towing carriage. The output from the instrument was recorded by the pen-writing recorder. The results obtained in case where the direction of the two axes of the sensor were aligned with the direction of the movement of carriage are shown in Fig. 6. In this figure, the ordinate and the abscissa are the values of output

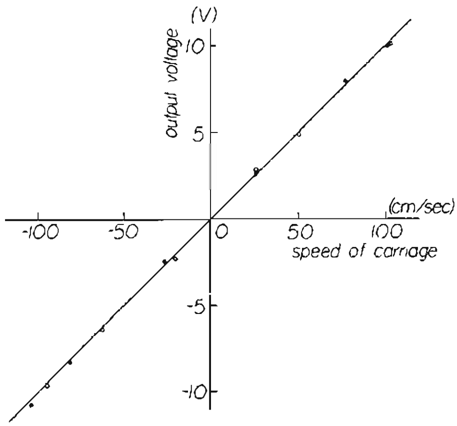

Fig. 6. Calibration curves of the sing-around flowmeter for output voltage vs. speed of the towing carriage. Two axes of the sensor are aligned with the direction of the movement of the towing carriage.
●: u-component, ○: v-component.

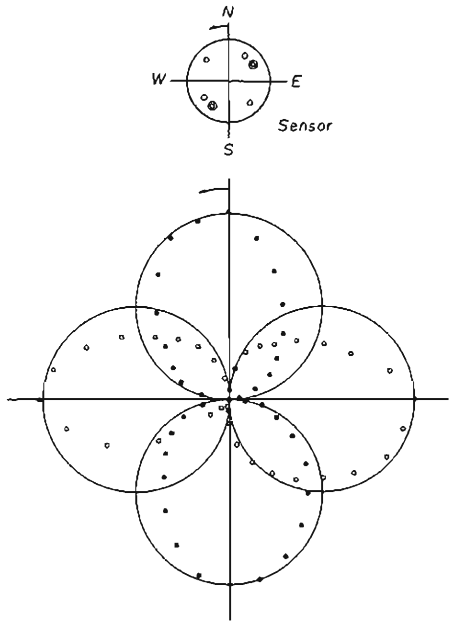

Fig. 7. Directional diagram of the sing-around flowmeter. Circles are necessary diagrams. Speed of the towing carriage is 30 cm/sec.
●: readings of NS-component of velocity.
○: readings of EW-component of velocity.

voltage and the speed of carriage measured, respectively. Both components of the instrument have good linearity over whole range of velocity from negative to positive. Figure 7 shows the two orthogonal components of velocity measured simultaneously for the constant flow coming from various directions. In the case where the flow direction is not aligned with the axis of the sensor, both values measured become smaller than the theoretical ones represented by circles as shown in the figure. This cause of error seems to result from the existence of the wakes of the transducers or supporting rods. If there is a wake in the acoustic path, its effect on the propagation time of the sonic waves is to be estimated by assuming the existence of a small domain of still water in its path. Denoting the equivalent length of such a small domain Δl_1, and Δl_2, for each pair of sing-around systems, respectively, the sing-around frequencies are given by

$$f_1=\frac{1}{\dfrac{l-\Delta l_1}{c-V\cos\theta}+\dfrac{\Delta l_1}{c}}, \qquad f_2=\frac{1}{\dfrac{l-\Delta l_2}{c+V\cos\theta}+\dfrac{\Delta l_2}{c}}. \tag{10}$$

Therefore, the effect of the wake on the sing-around frequency becomes,

$$\frac{\Delta f'}{\Delta f}=1-\frac{\Delta l_1+\Delta l_2}{2l}. \tag{11}$$

It is found from eq. (11) that the existence of the wakes in the acoustic path generally results in the decrease of the difference of the sing-around frequencies. This relationship and the difference of the length of rods as shown in Fig. 4 and Photo. 1, make it possible to understand the error shown in Fig. 7. Therefore, the instrument presented here is available for measuring the eddies moving with the mean flow, the direction of which is aligned with the axis of the sensor.

3. The ultrasonic flowmeter based on the method of pulse-time difference

In the sing-around method presented above, the error due to noise is serious, because the noise received by the receiver acts as the trigger wave if its amplitude is larger than the trigger level and, as a result, the next pulse is emitted from the transmitter. The method of detecting the phase lag by the use of the continuous wave, which is called the method of phase-difference, seems to be the most suitable for obtaining an analogue output of velocity. The characteristics of such an instrument are determined by those of the detecting circuit of the phase difference. It is difficult, however, at present to ensure the linearity of the circuit of the detection of the phase difference within an error of less than several percent. The time constant of the phase difference meter commonly used is not small that it can be used for measuring the turbulent velocity. Furthermore, in the method of phase difference, the distortion of the wave form during its propagation through the medium become a cause of error, and the frequency of the sonic wave used should be changed by the interval between the transmitter and the receiver and the extent of velocity. An increase of frequency results from the shortening of the acoustic path makes difficulties in detecting the phase difference. The method of pulse-time difference is the one which is least affected by noise, but when the propagation time of the acoustic pulse is short, this method has the defect that the error of measurement grows larger. It is difficult at the present technical level of electronics for the interval between the transmitter and the receiver to be made narrower than several centimeters. Furthermore, it is rather difficult to obtain the analogue output in comparison with other methods.

1) *Principle of the method of pulse-time difference*

The arrangement of the transmitting-receiving transducer in the ultrasonic flowmeter based on the method of pulse-time difference is shown in Fig. 8. The propagation time of the sonic wave in the normal or opposite direction along the same acoustic path is detected by alternately switching the direction of an electro-acoustic system. The V-shaped arrangement of the transmitting-receiving transducers as shown in Fig. 8 is a consequence of the device to make the acoustic path longer in order to maintain high accuracy of

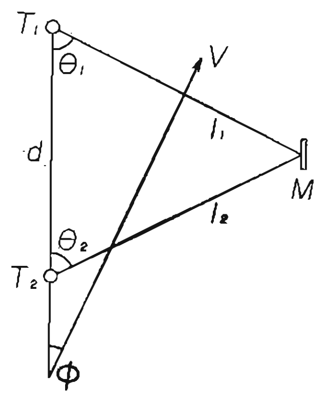

Fig. 8. Arrangement of the transmitting-receiving transducers T_1 and T_2, and reflector M of the pulse-time difference flowmeter. d is the distance between T_1 and T_2.

measurement and the small size of the sensor. The acoustic pulse emitted from the transducer T_1 is reflected by the reflector M and arrives at the transducer T_2. This propagation time is denoted by t_1, and the propagation time in the opposite direction t_2.

$$\left.\begin{aligned} t_1 &= \frac{l_1}{c-V\cos(\theta_1+\phi)} + \frac{l_2}{c-V\cos(\theta_2-\phi)} + \tau_\varepsilon, \\ t_2 &= \frac{l_2}{c+V\cos(\theta_2-\phi)} + \frac{l_1}{c+V\cos(\theta_1+\phi)} + \tau_\varepsilon, \end{aligned}\right\} \tag{12}$$

where τ_ε is the electric delay time already mentioned. In these expressions, the velocity distribution is assumed to be uniform in the domain under consideration. After the approximation that $(V/c)^2 \ll 1$, the difference of both propagation times is,

$$t_1 - t_2 = \frac{2dV\cos\phi}{c^2}. \tag{13}$$

On the other hand, their sum is,

$$t_1 + t_2 = \frac{2(l_1+l_2)}{c} + 2\tau_\varepsilon. \tag{14}$$

Therefore,

$$V\cos\phi = \frac{(l_1+l_2)^2}{d} \cdot \frac{t_1-t_2}{(t_1+t_2-2\tau_\varepsilon)^2}. \tag{15}$$

The velocity of the water can be accurately obtained by the detection of the difference and the sum of the propagation times in two directions.

In this method, the influence of change of the propagation distance of the acoustic wave to the detected value of velocity is small compared with that in the sing-around method. Assuming, for the sake of simplicity, that the transmitting-receiving transducers T_1 and T_2 are placed at interval l along the flow, the propagation times of the acoustic pulse in the downstrream and upstream directions are, respectively,

$$t_1 = \frac{l}{c-V}, \qquad t_2 = \frac{l}{c+V}. \tag{16}$$

The difference of these is given,

$$\Delta t = t_1 - t_2 = \frac{2Vl}{c^2}. \tag{17}$$

A slight change of the acoustic path $\pm \Delta l$ reduces that,

$$t_1' = \frac{l \pm \Delta l}{c-V}, \qquad t_2' = \frac{l \pm \Delta l}{c+V}, \qquad \Delta t' = t_1' - t_2' = \frac{2Vl(1\pm\varepsilon)}{c^2}, \tag{18}$$

where $\varepsilon = \Delta l / l$. Therefore,

$$\frac{\Delta t'}{\Delta t} = 1 \pm \varepsilon. \tag{19}$$

Since the acoustic path l is about 6 cm in the instrument developed here, a change of the interval of the acoustic path of about 1 mm gives an error of only 2% of the velocity value. From this point of view, the method of pulse-time difference is superior to the sing-around method.

2) Instrumentation

The sensor is shown in Fig. 9 and Photo. 2. The transducers and the reflector are mounted at the end of the rods 2~4 mm in diameter and 7 cm in length. Three rods are arranged so that $\overline{T_1M}=\overline{T_2M}=3$ cm and $\angle T_1MT_2=90°$. The transducers are made of a barium-titanate element 2×4 mm and the reflector is a stainless steel disc 7 mm in diameter.

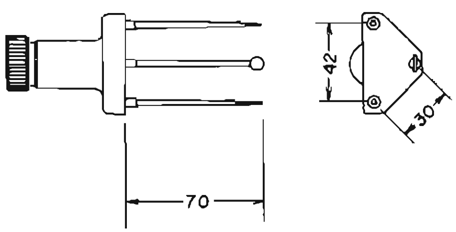

Fig. 9. Sensor of the pulse-time difference flowmeter (mm).

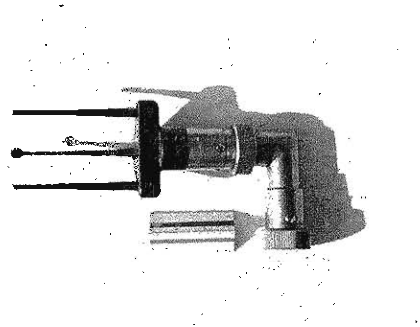

Photo. 2. Sensor of the pulse-time difference flowmeter.

The simplified block diagram of the instrument is shown in Fig. 10. An outline of the action of this flowmeter is as follows. The power amplifier produces a pulse of about 40 V amplitude and 20 nanosec duration. This pulse is emitted from the transducer T_1 towards the reflector M, and received by the transducer T_2 after reflection at M. The pulse received by the transducer T_2 is amplified by the head amplifier and fed to the reshaping circuit of the wave in order to be transformed into a square wave pulse. This pulse feeds a signal to the self-running circuit acting synchronously and also to the power amplifier to supply the electric energy to the transducer. The process is repeated alternately. That is, the acoustic pulse go and return on the same path. After the correction for the velocity of sound in the indicator, the analogue signal is fed to the low-pass filter and the output for a magnetic tape

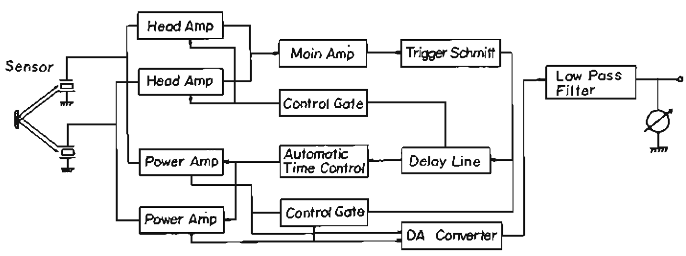

Fig. 10. Simplified block diagram of the pulse-time difference flowmeter.

recorder, a pen-writing recorder and an electromagnetic oscillograph are obtained.

The main characteristics of the instrument are the following. The measuring ranges of the velocity are 0~±0.5 m/sec, 0~±1.0 m/sec and 0~±1.5 m/sec, and output voltages are 0~±1V, 0~±2V and 0~±3V, respectively. The frequency of the ultrasonic wave is about 3 MHz. The temperature range in operation is 0°C~30°C. The cut-off frequencies of the low-pass filter are 0.1, 0.5, 1.0, 10 and 30 Hz. The power source is AC 100 V, 60 Hz.

3) Calibration

The calibration of the instrument is carried out in the same manner as described in the case of the sing-around flowmeter. The results are shown in Fig. 11 and Fig. 12. In the directional diagram constructed in polar coordinate, a deviation of the measured values from the circles representing the theoretical value is seen. A cause of this deviation is the existence of wakes due to the supporting rods, as stated before.

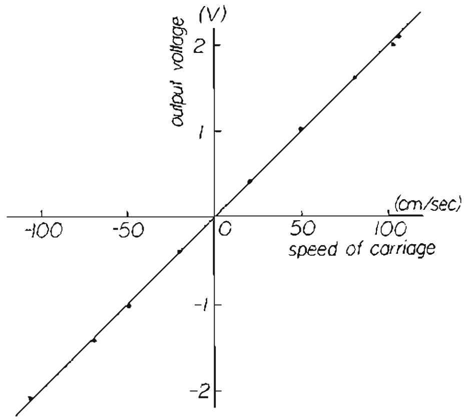

Fig. 11. Calibration curve of the pulse-time difference flowmeter for output voltage vs. speed of the towing carriage. The axis of the sensor is aligned with the moving direction of the carriage.

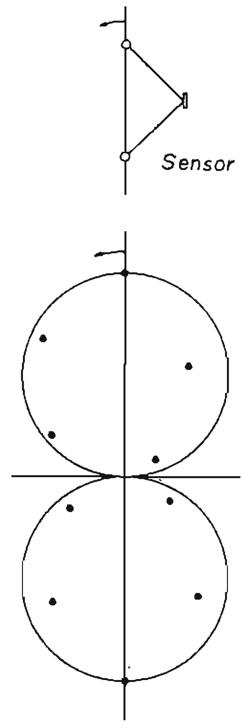

Fig. 12. Directional diagram of the pulse-time difference flowmeter. Circles are necessary diagrams. Speed of the towing carriage is 30 cm/sec.

4. Measurement of river turbulence by ultrasonic flowmeters

1) The influence of the size of the sensor and the duration of the observation on the spectrum

The measuring instrument has inertia and the duration of the observation is not infinite. They therefore give an incomplete, or distorted picture of the river turbulence to be measured. There appears, as a result, a modification of the spectrum of turbulence at both ranges of high and low frequencies. An evaluation of the modification is made in the following.

The inertia of the ultrasonic flowmeter presented here is practically negligible from the viewpoint of time, but a spatial averaging throughout the size of the sensor obviously occurs. It may be possible under an appropriate assumption that the effect of the sensor is represented by a time scale. That is, this is carried out by weighting the spectrum by the factor $A(n, s)$,

$$A(n, s)=\frac{\sin^2 \pi ns}{(\pi ns)^2}, \tag{20}$$

where s is the averaging time interval corresponding to the size of the sensor. Similarly the effect of the duration of the observation is to weight the spectrum by a complementary factor $B(n, T_*)$,

$$B(n, T_*)=1-\frac{\sin^2 \pi nT_*}{(\pi nT_*)^2}, \tag{21}$$

where T_* is the duration of the observation. Therefore the dual effect of both size and duration on the variance of turbulent velocity is given by the relationship[7],

$$\overline{u'^2}_{obs}=\overline{u'^2}\int_0^\infty F(n)A(n, s)B(n, T_*)dn, \tag{22}$$

where $\overline{u'^2}_{obs}$ is the variance obtained by averaging over the time interval, s, corresponding to the size of the sensor and over the duration of the observation, T_*. And $\overline{u'^2}$ is the true variance of the velocity field given by

$$u'^2=\overline{u'^2}\int_0^\infty F(n)dn, \tag{23}$$

where $F(n)$ is the normalized energy spectrum and is related to a coefficient of correlation $R(t)$ as is well known,

$$F(n)=4\int_0^\infty R(t) \cos 2\pi ntdt. \tag{24}$$

It has been found that the correlation coefficient of river turbulence can often be represented approximately by the exponentially decaying function[1],

$$R(t)=\exp\left(-\frac{t}{T_E}\right), \tag{25}$$

where T_E is an Eulerian integral time scale. The spectrum corresponding to this correlation becomes,

$$F(n)=\frac{4T_E}{1+(2\pi T_E n)^2}. \tag{26}$$

Substitution of eqs. (20), (21) and (26) into (22) yields the ratio of the measured variance to the true variance,

$$\frac{\overline{u'^2}_{obs}}{\overline{u'^2}}=4\int_0^\infty \frac{T_E}{1+(2\pi)^2 T_E{}^2 n^2}\left(1-\frac{\sin^2 \pi nT_*}{(\pi nT_*)^2}\right)\frac{\sin^2 \pi ns}{(\pi ns)^2}dn. \tag{27}$$

Equation (27) is numerically calculated and the results are shown in Figs. 13 and 14. A contribution to the variance does not show a remarkable increase

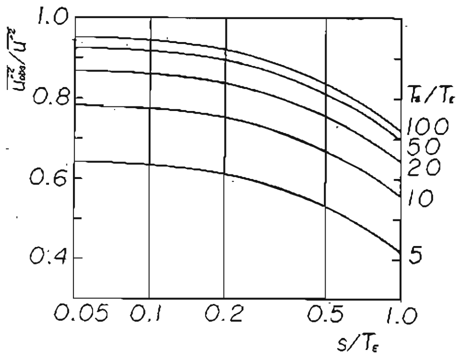

Fig. 13. Decrease of variance ratio between measured and true values with increasing s/T_E for various T_*/T_E, where s, T_* and T_E are an averaging time, duration of the observation and a Eulerian integral time scale, respectively.

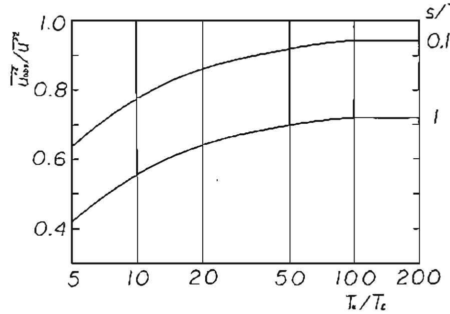

Fig. 14. Increase of variance ratio between measured and true values with increasing T_*/T_E.

in the regions, $s/T_E<0.1$ and $T_*/T_E>100$, in spite of the increase of T_*/T_E and decrease of s/T_E. It is concluded, therefore that it is practical to make a plan of observation under the conditions,

$$s \leq 0.1 T_E, \tag{28}$$

$$T_* \geq 100 T_E. \tag{29}$$

The characteristic size of the sensor of the ultrasonic flowmeters developed here is about $d=3$ cm. In the measurement of a longitudinal component of velocity, this size can be transformed into an averaging time interval by the use of the frozen turbulence hypothesis,

$$s = \frac{d}{\bar{u}}, \tag{30}$$

where $\bar{u}$ is a mean velocity of the longitudinal component. On the other hand, the observation of river turbulence has shown that the Eulerian integral time scale is represented approximately as[1],

$$T_E \simeq 2\frac{z}{\bar{u}}, \tag{31}$$

where z is the height from the bottom of the flow. In conclusion, the observation of river turbulence by the ultrasonic flowmeter should at least be made under the satisfaction of the conditions,

$$T_* \geq 200\frac{z}{\bar{u}}, \qquad z \geq 5d = 15\,\text{cm}. \tag{32}$$

2) *Example of the results of measurement*

Typical examples of records are shown in Figs. 15 and 16. The former shows the simultaneous record of the longitudinal and vertical component of turbulent velocity measured by the sing-around flowmeter in a natural river.

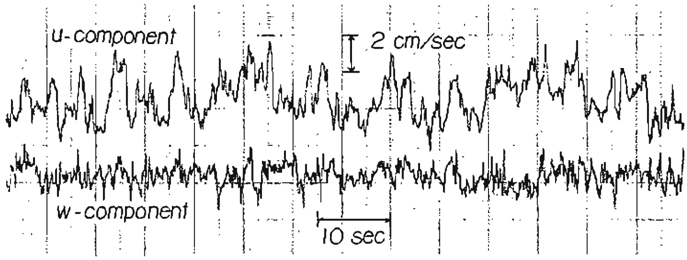

Fig. 15. Typical example of the records of u' and w' measured by the sing-around flowmeter in a river current.

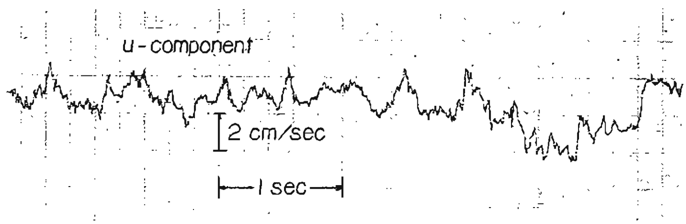

Fig. 16. Typical example of the record of longitudinal velocity measured by the pulse-time difference flowmeter in a river current.

The latter the record of the longitudinal velocity by the pulse-time difference flowmeter.

The observation to determine the distribution of the Reynolds stresses in a natural river is made in the Uji river. The measuring part is a straight and uniform channel, about 2 m in depth and 100 m in width, with a fairly regular bottom. Simultaneous measurements of u' and w', the longitudinal and vertical components of turbulent velocity are carried out at various depths[8]. Figure 17 shows an example of the power spectra of u' and w', and negative cospectrum between u' and w'. The mean velocity $\bar{u}$ is about 1 m/sec, and the r.m.s. values of u' are of the order of 10% of $\bar{u}$, while those of w' are about 6%. At the center of the depth, the Reynolds stress is about 60 dyn/cm², and the friction velocity is nearly equal to the r.m.s. value of w'. Auto- and cross-spectral analyses show that there exists a region satisfying the law of $-5/3$ power in the spectrum of u' and w' predicted by Kolmogorov's theory of turbulence[9], while the cospectrum between u' and w' nearly satisfies the law of $-7/3$ power.

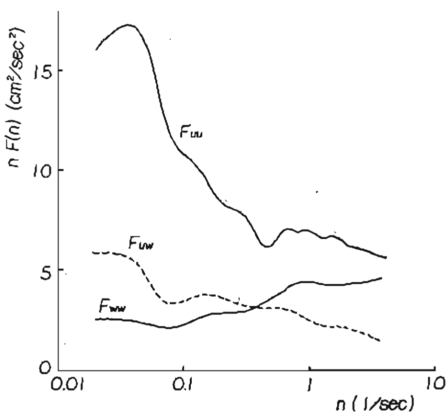

Fig. 17. Typical example of the energy spectra of u' and w', and negative cospectrum between u' and w'.

In analysing the results measured, there are a great deal of data. Since, therefore, efficient data processing is strongly desired, a system consisting of magnetic tape recorder, a high speed A-D convertor, a high speed tape puncher and a high speed digital computer with a large capacity is used with effect.

5. Conclusion

Two kinds of ultrasonic flowmeters with a small size sensor have been developed for measuring river turbulence. It has been ascertained from the results of both calibration tests and field observation that the ultrasonic flowmeter is suitable for the field observation of river turbulence. However, the instruments developed here have room for improvement. For instance, in the sing-around flowmeter, the sensor should be modified so as to consist of four transducers in order to reduce the undesirable influence of the wake, because one component of velocity can be measured by one pair of transducers by alternately switching the direction of sing-around at appropriate time intervals. In the pulse-time difference flowmeter, there are also several features that need to be improved in order to increase the accuracy of detection of the pulse-time difference.

In the case of the design of the ultrasonic flowmeter, the choice of the method, arrangement of transducers, determination of the dimension of sensor and so forth, must be taken into consideration according to the purpose for which it is to be used. The future of the ultrasonic flowmeter may be supposed to have very bright prospects as more technical advances are made in the field of electronics.

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