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FUJI ULTRASONIC FLOWMETER SERIES

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I. INTRODUCTION

FUJI ultrasonic flowmeter, with its prominent features, has already been recorded in number of installations with several hundred units since marketed first, and it is being used positively for service water, sewerage, industrial water and agricultural water facilities.

In the meantime, in step with the high-degree and diversified applications of water treatment facilities along with strengthening of the maintenance control, the role of instrumentation has become significant increasingly and in addition, it has recently developed into new aspects including availability at wider range, energy saving, saving natural resources and so on. Furthermore, electronics backing up the measurement control technology has also made great strides.

In this report, the new ultrasonic flowmeter series completed by utilizing fully the latest electronics to satisfy the needs for the ultrasonic flowmeter will be introduced. These new series have contributed to more expansion of the application range of flowmeter.

(1) Extensive applications to sewage with high reliability.
(2) Higher accuracy.
(3) Applicability to eccentric flow.
(4) Measurement of open channel flow.

Table 1 outlines the Fuji ultrasonic flowmeter series.

II. MEASURING PRINCIPLE OF ULTRASONIC FLOWMETER

Ultrasonic transducers (transmitter & receiver) are placed at upper stream and downstream sides of flow and ultrasonic pulses are propagated obliquely as shown in *Fig. 1.*

Time difference produced due to flow between propagation time of ultrasonic pulses from upper stream to downstream side, t_1 and propagation time of the pulses from downstream to upper stream, t_2 is utilized. Assuming the flow velocity is V and acoustic velocity is C, t_1 and t_2 are expressed as follows:

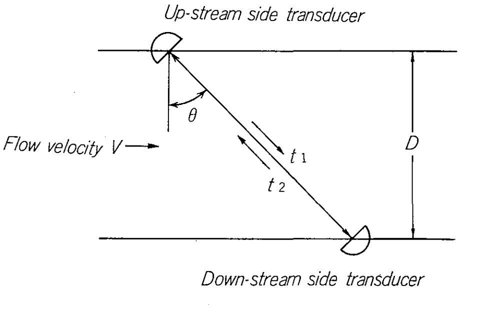


Fig. 1 Principle of ultrasonic flowmeter

Table 1 Fuji ultrasonic flowmeter series

For use	Article	Type		Feature	Specification
		Detector	Transmitter		
Pipe line	CLAMP-ON type Ultrasonic Flowmeter	FLG	FLF (or) FLH	• Flow rate can be measured from the Outside of piping • Easy installation	• Pipe bore: more than 200 mmϕ • Accuracy: 1 ~ 1.5%
	PIPE-MOUNTED type Ultrasonic Flowmeter	FLE		• High accuracy • Easy handling, like an Elec-Magnetic flowmeter	• Pipe bore: 300 ~ 800 mmϕ • Accuracy: 1%
Open channel	Ultrasonic Flow-Velocity meter	FLX		• No obstacles to the flow • Multi-scanning method	• Channel width: more than 0.5 m • Accuracy: 1 ~ 1.5%
	Ultrasonic Liquid Level meter	FQG	FQH	• Non-contact measurement • Easy installation, easy maintenance	• Span: 0 ~ 0.2 m . . . 0 ~ 10 m • Accuracy: 1%
	Digital Controller	–	PRM	• Multi-functions • High accuracy	• Linearity: 0.2%

$$t_1 = \frac{D/\cos\theta}{C + V\sin\theta}, \; t_2 = \frac{D/\cos\theta}{C - V\sin\theta} \quad \ldots\ldots\ldots (1)$$

Thus, time difference occurs due to V between t_1 and t_2. But in a simple subtraction of $t_2 - t_1$, acoustic velocity C remains in the flow coefficient. Therefore, subtraction is made by making t_1 and t_2 reciprocate respectively. Namely, the following equation is obtained;

$$\frac{1}{t_1} - \frac{1}{t_2} = \frac{C + V\sin\theta}{D/\cos\theta} - \frac{C - V\sin\theta}{D/\cos\theta} = \frac{2V\sin\theta}{D/\cos\theta}$$

$$= \frac{\sin 2\theta}{D} \cdot V \quad \ldots\ldots\ldots (2)$$

By giving dimension D and angle θ, the flow velocity can be detected. By making subtraction with propagation time as a reciprocal number as given above, flow coefficient not including acoustic velocity C in fluid is obtained, thus enabling measurement without depending upon the temperature and composition of fluid.

A detailed circuit system will be described hereunder. FUJI's TLL (Time Locked Loop) system has been established by applying the idea of PLL (Phase Locked Loop) circuit already known in the circuit technology. *Fig. 2* shows a block diagram of the principle of TLL system flow measurement.

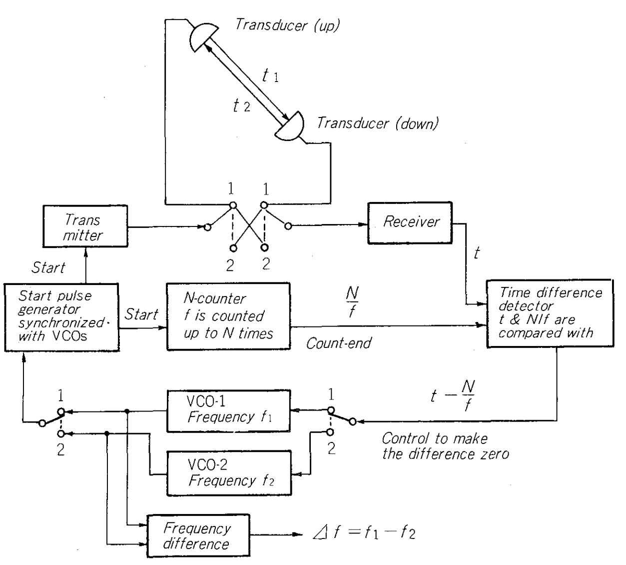


Fig. 2 Principle of TLL method

Output signal Δf measured by TLL method is expressed as follows.

$$\Delta f = f_1 - f_2 = N\left(\frac{1}{t_1} - \frac{1}{t_2}\right) = \frac{N\sin 2\theta}{D} \cdot V \quad \ldots\ldots (3)$$

Thus the signal proportional to flow velocity V and not including acoustic velocity C can be obtained. Further, by comparing f_1 with f_2, the flow direction can be detected.

Ultrasonic flowmeter thus provides measurement with only its geometrical dimensions and angle, and setting constants of circuits, hence it is widely applicable to fluids for which ultrasonic propagation is available. In addition, the ultrasonic flowmeter has following advantages:

(1) Average flow velocity on the survey line (ultrasonic propagation route) can be obtained and the output characteristic is linear from 0 (zero) of flow rate.
(2) The flowmeter can be installed without disturbing flow. (Measurable from the outside wall of pipe, or from the wall face of watercourse.)
(3) Measurable without contacting fluids.
(4) Maintenance is easy. (Simple structure of the detector makes possible to replace readily.)
(5) Even for a large-bore pipe and flow rate, measurement is achieved at low costs.

III. COUNTERMEASURE FOR SEWAGE

TLL system possesses an attractive feature for "dirty water". Heretofore, it has been generally accepted that the conventional ultrasonic flowmeters are not adaptable to sewage, however this FUJI-make ultrasonic flowmeter has overthrown such unfavourable repute and has been used widely even for sewage. Some examples of circuits for ensuring reliability against sewage will be introduced.

1. Receive-Miss-Hold Circuit

This is a countermeasure for a case where propagation of sonic wave fails on occasion. In a sewerage plant, foreign substances are mixed in fluid whereby ultrasonic wave propagation route is obstructed, and if sonic wave can no longer be propagated, a receive-miss detecting circuit operates to hold VCO frequencies f_1 and f_2. Accordingly, the flow velocity signal Δf holds the value as it has been so far and the effect on the output due to cut-off of ultrasonic beam can be eliminated.

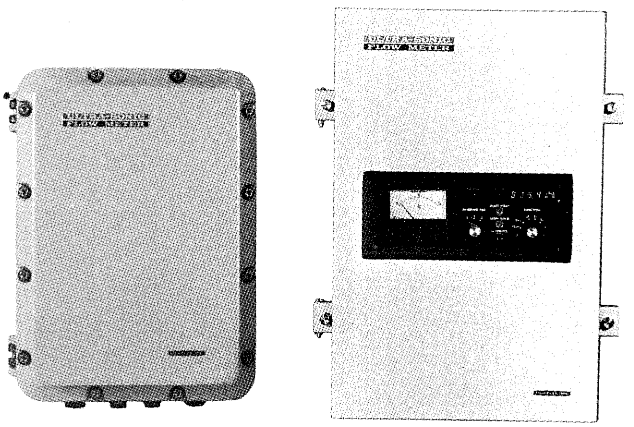
2. Double Trigger Circuit

This is a countermeasure for a case where attenuation factor of sonic wave greatly fluctuates. In a sludge treatment plant, as sludge density in fluid changes, attenuation factor of ultrasonic wave in propagation also varies greatly. If attenuation factor varies greatly, the waveform received is deformed.

If waveform is subject to deformation in this way while the reaching time of receiving wave is being picked up at a fixed trigger level, there is a case where time detection error called a trigger miss is generated. If trigger miss takes place in a great number in measurement frequency, it may lead to indication error, instability or scale-out of output. The double trigger circuit is incorporating two different voltage levels as trigger levels, in order to prevent grigger miss by changing the trigger level when received waveform varies, and more optimum trigger level in two is selected automatically. Therefore, stable flow measurement is possible even when sludge density changes, or when a small amount of bubles is contained.

Table 2 Specifications of transmitters of ultrasonic flowmeters

Item		FLF transmitter	FLH transmitter
Measuring method		TLL (Time Locked Loop) system	
Measuring flow velocity range		0 ~ 1 m/s (minimum span) ~ 0 ~ 10 m/s (maximum span)	
Analog signal damping (90% response time)		1, 10, 30, 100 sec. selectable	1, 3, 10, 30, 100 sec. selectable
Countermeasure for sewerage		Receive Miss-Hold circuit, Double trigger circuit, TLL self-diagnostic circuit is built in.	
Power supply		AC 100V, 50/60 Hz (AC 110, 200 or 220V is also usable)	
Power consumption		About 25 VA	About 50 VA
Case structure		(A type case) Submergible structure (JIS0920) (B type case) Indoor dust-proof structure	Indoor dust-proof structure
Weight		(A type case) Approx. 17 kg (B type case) Approx. 14 kg	Approx. 19 kg
Output signals	Analog	DC 4 ~ 20 mA (10 ~ 50 mA is also available)	
	Integrating pulse	Addable (E)	Relay contact output Integration unit; Optionally settable
	High-speed pulse	None	Transistor output (addable)
	Flow direction	Addable (F)	Contact output
	Abnormal alarm	Addable (H)	Contact output
	Bidirectional analog	Addable (G)	None
Indicator section inside transmitter		None	Analog indicator
		Operation check, LED-display	4-digit LED indication Flow direction, LED display Operation check, LED display
Additional functions		Only one of these functions above E, F, G, H, is addable	Analog range switching input circuit Two-measuring line selector circuit
Connection with detector		Can be combined with either clamp-on type (FLG), pipe-mounted type (FLE), or velocity meter for open channel (FLX).	



(a) type-FLF (b) type-FLH

Fig. 3 Transmitters of ultrasonic flowmeter

3. TLL Self-Diagnostic Circuit

This circuit is for watching whether the operation of the whole basic circuit system of TLL is stable, and it is so constructed as to control final output signal only when the operation is stable and hold in case where the operation is unstable. This circuit is a so-called self-diagnosing circuit, since it is acting to judge the stability of the closed loop through watching of the operation in the time difference detecting circuit. This circuit has another feature that response characteristic is not sacrificed, because even though flow rate varies sharply, it is not judged to be abnormal.

Therefore, even in a case of a very series attenuation, stable output is assured.

These circuit directed for sewage are incorporated in a newly-developed FLF-type transmitter and also, they can be fitted to FLH-type transmitter, too. *Fig. 3* shows the external view of both types of transmitters. This FLF-type transmitter has a water-proof construction to enable installing even in subterranean pits and its wider applications are expected together with FLH-type one.

Table 2 lists the main specifications of these transmitters.

IV. FLOW MEASUREMENT IN PIPE LINES

The clamp-on type and the pipe-mounted type are available for a pipe line use. *Table 3* lists the main specifications of these detectors.

1. Clamp-on type detector (type-FLG)

Flow measurement can be made just only by fitting the detectors on the outside wall of piping without contacting fluid flowing inside.

This type which can be installed on the existing piping in operation, displays its fullest functions as a ultrasonic flowmeter. *Fig. 4* is the basic arrangement of transducers and *Fig. 5*, the installation aspect in a field. As shown in *Fig. 4*, the time required until ultrasonic pulse is received follwoing its emmission comprises the propagation time in

Table 3 Specifications of detectors for pipe lines

Item		Clamp-on type, FLG	Pipe-mounted type, FLE
Fluids measured		Raw water, pure water, industrial water, agricultural water, sea water, etc.	
Temperature of fluids		0 ~ 50 °C	
Measuring pipe	Bore size	more than 200 mmφ	300 ~800 mmφ
	Material	Steel, cast iron, stainless steel	Steel or stainless steel
Installation		Mounted to outer wall of existing pipe	Flange connection to the pipe-line
Accuracy		±1.0% (large bore size) ±1.5% (small bore size)	±1.0%
Installation condition		Straight pipe portion: Upstream side: more than 10 D Downstream side: more than 5 D	
Ambient temperature, humidity		−10 ~ +60 °C, less than 95% RH	
Water-proof structure		Submergible type (JIS C 0920)	
Weight		Approx. 10 kg x 2	Approx. 85 ~ 400 kg (differs according to the pipe size)

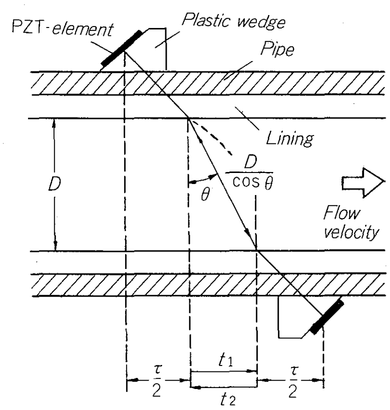


Fig. 4 Basic arrangement of clamp-on transducers

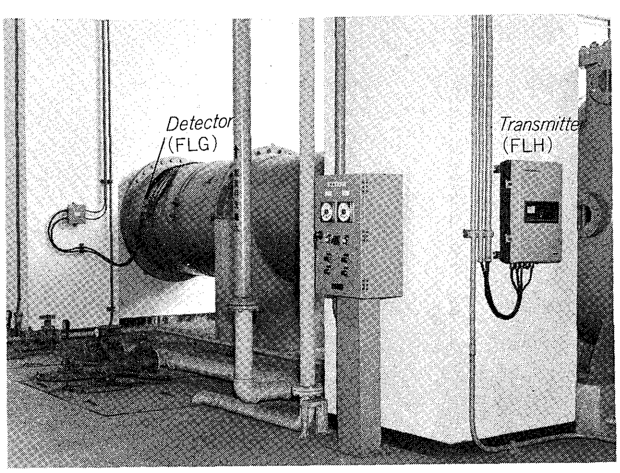


Fig. 5 Installation aspect of ultrasonic flowmeter (type-FLG, FLH)

the pipe material, lining and plastic wedge (these are summed up as τ) in addition to t_1 and t_2, so that the time amount to $t_1 + \tau$ and $t_2 + \tau$ in the forward and reverse directions. Accordingly, taking difference with $t_1 + \tau$ and $t_2 + \tau$ as reciprocals, Δf is expressed as follows;

$$\Delta f = \frac{1}{t_1 + \tau} - \frac{1}{t_2 - \tau} = \frac{N \sin 2\theta}{D} \left(1 + \frac{\tau C \cos\theta}{D}\right)^{-2} \cdot V \quad \ldots\ldots\ldots\ldots\ldots (4)$$

And, a term including τ and C comes in the coefficient, which has a temperature dependent character. In order to compensate the propagation time other than in fluid, TLL system employs a method which cancels τ by providing a delay circuit having the set time identical to τ at the post-stage of N counter. Namely, the count end signal N/f is delayed by τ, and $N/f + \tau$ and $t + \tau$ are compared with each other at the time difference detecting circuit. Then, it is so controlled that $N/f + \tau$ becomes equal to $t + \tau$, $N/f + \tau = t + \tau$ and as a result, N/f becomes equal to t, $N/f = t$, accordingly, τ is cancelled and the equation (3) is obtained.

Flow rate q in the pipe line is given by the follwoing equation by multiplying flow velocity obtained from the equation (5) by the sectional area of pipe and further, by correcting flow velocity distribution in diametral direction.

$$q = \frac{1}{k} \cdot \frac{\pi D^2}{4} \cdot \frac{D}{N \sin 2\theta} \cdot \Delta f \quad \ldots\ldots\ldots\ldots\ldots (5)$$

k is correction coefficient of flow velocity distribution and a function of Reynold's number.

2. Pipe-Mounted Type Detector (Type-FLE)

The smaller the bore of the pipe becomes, the lesser the propagation time becomes, and accordingly, the time difference due to flow is also lesser, therefore ultrasonic flowmeters have a tendency not to be ensured high accuracy in small bore size. However, thanks to the detector of this type, high-accuracy measurement has become possible free from the above difficulty, even in small- and medium-bores.

Fig. 6 shows the external view (bore of 300 mm) and *Fig. 7*, the structure of the detector. In said clamp-on detector (FLG), the angle of survey line θ is restricted to about 23 ° because of refraction at an interface of metallic pipe and liquid according to Snell's law, and at a large angle, the propagation fails due to total reflection. However, when a wet probe is used as this type, angle of survey line θ is freely selectable, thus enabling the detector to be installed 45 °. As understood from the equation (3), the larger the survey

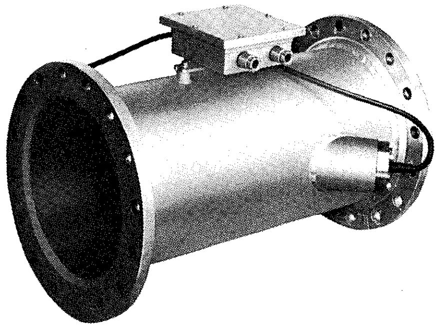


Fig. 6 Pipe-mounted type detector (type-FLE)

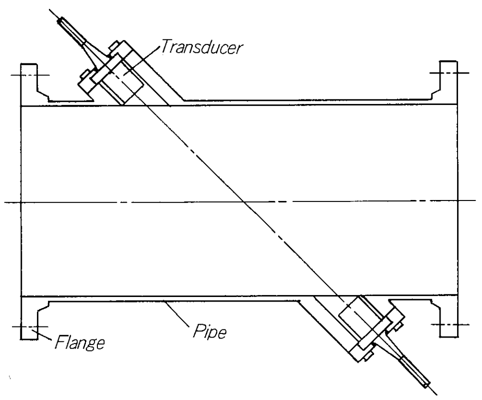


Fig. 7 Structure of pipe-mounted type detector (type-FLE)

line angle θ is, the larger the coefficient becomes and resolving power betters and further, high-accuracy measurement can be realized even by a small-bore flowmeter.

3. Dual Pass-Way Method (Measurement of Eccentric Flow)

As described in the item of principle, ultrasonic flowmeter measures the mean flow velocity on survey line, obliquely to the flowing, therefore as a prerequisite, flow velocity V has to be in parallel with the water course. Therefore, it is necessary that the piping has a straight pipe portion of more than 10 times length of bore on the upper stream side and 5 times on the downstream side. However, in actual plants, this requirement is not always satisfied and there is a case where a flow not in parallel with the watercourse, i.e., an eccentric flow is generated and it causes measurement error. This method has been thought up aiming at providing a high-accuracy measurement even for such plants.

Fig. 8 shows the principle drawing. Two sets of ultrasonic transducers are placed within a plane including the axis of water course so that they become symmetrical to the axis, and survey lines A and B are formed.

When flow velocity vector V is not parallel to the axis, a projecting component to the survey line A becomes v_a. The result is that flow velocity measurement value becomes V_A and measurement value with the survey line B becomes V_B respectively. Thus in case of an eccentric flowing, the

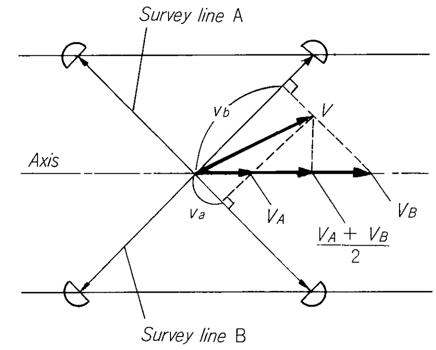


Fig. 8 Principle of dual pass-way method

difference occurs in measured values according to the direc-
difference occurs in measured values according to the direc-
tion of survey lines, however, by taking the average, $\frac{V_A+V_B}{2}$, of 2 survey lines placed symmetrically the component in the axial direction can be obtained, thus making possible to measure correctly.

In actual plants, another complexed flow takes place, therefore it is difficult to theorize strictly. In the field test in such plants, it has been ascertained that the dual pass-ways method provides such effect that error caused in a single pass-way method, can be reduced to 1/10 to 1/20.

This dual pass-ways method is adaptable to either foregoing clamp-on or pipe-mounted type detector and also applicable to the flow measurement in open channels described next.

V. FLOW MEASUREMENT IN OPEN CHANNELS

1. Principle of Measurement

As conventional flow measurement methods in open channels, i.e., water channel having free water surface, flume-type and weir-type are already known. In both methods, flow rate is obtained by measuring water level with a throat or an overflow weir installed in the course of water channel.

In the ultrasonic method, as shown in *Fig. 9*, flow velocity is taken through an ultrasonic velocity meter installed at both banks of water channel, and the sectional area of water channel is obtained by means of ultrasonic level meter installed above water surface. Flow rate is obtained

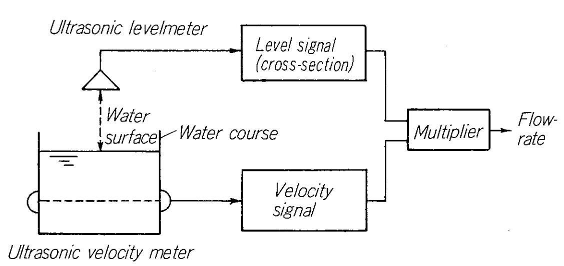


Fig. 9 Principle of flow measurement for open channels

by arithmetic operation of the flow velocity multiplied by the sectional area.

The ultrasonic method has such advantages that the installation of detectors is easy, both for level and velocity and it is not necessary to deform the shape of the channel and further that there is no obstacle to flow. Then it is broadly applicable, for example, to raw water in water treatment plant, industrial water, agricultural water, sewage, etc. and in particular, it is convenient for measurement in the existing water channels.

2. Measurement of Water Level — Ultrasonic Level Meter (Type-FQG and FQH) —

By measuring the time required from the emission of ultrasonic pulse to the reception of the echoe reflected from water surface the distance to the water surface is obtained. Assuming the distance is L and acoustic velocity in the air is C, ultrasonic propagation time t in both ways, is expressed as follows;

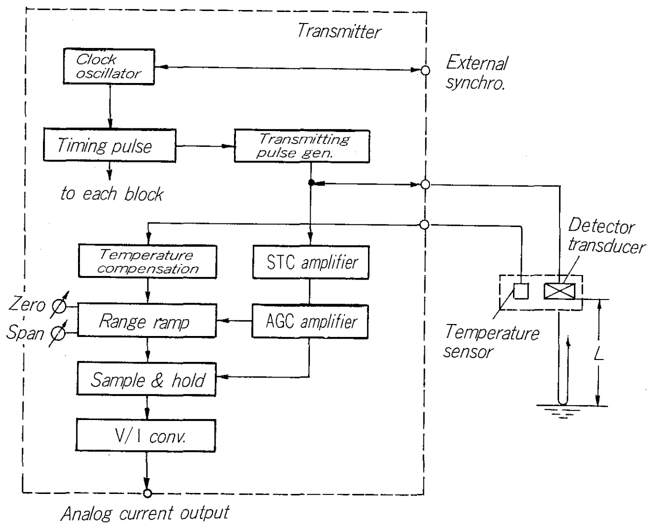


Fig. 10 Block diagram of ultrasonic level meter (type-FQH)

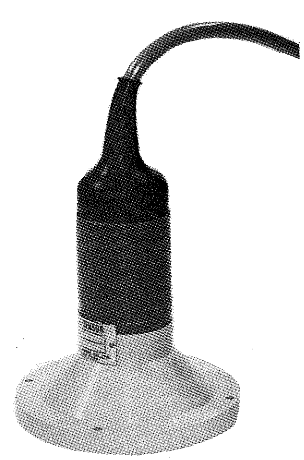


Fig. 11 FQG type detector of ultrasonic level meter

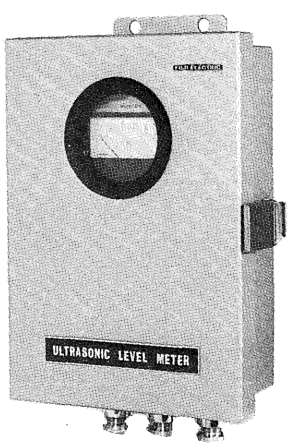


Fig. 12 FQH type transmitter of ultrasonic level meter

$t = \frac{2L}{C}$, Therefore, L becomes as follows;

$$L = \frac{Ct}{2} \quad \cdots\cdots (6)$$

The distance can be measured by measuring t when C is known. Acoustic velocity C in the air changes according to the temperature and is expressed as follows;

$C = 331.45 + 0.607T$ (m/s)

(T: Temperature °C)

Therefore, compensation may be made by measuring the temperature.

Fig. 10 illustrates the block diagram of measurement circuits.

Figs. 11 and *12* show the external views of the detector and transmitter of the ultrasonic level meter. Types FQG and FQH have been newly developed as a level meter exclusively used for liquid level measurement, and they have been made on the basis of ultrasonic level meter, types LM2 and LE2. Type FQG series are suitable to use for water treatment plants, as the respective detectors have a water-proof construction together with measuring span of 0 to 0.2 m, and to 10 m.

3. Measurement of Flow Velocity — Ultrasonic Velocity Meter (Type FLX and FLH (F)) —

As the walls of open channels are made of concrete in general, measurement of flow velocity from the outside walls is difficult. Therefore, the detector of velocity meter (FLX) is so constructed as to enable installing on the inside face of channel wall with the use of a wet type probe.

As the velocity meter transmitter, Type FLH or FLF is used commonly for pipe lines.

As stated in the item of principle, mean value of flow velocity in the survey line is measured, but generally, in open channels, there is distribution of flow velocity in the direction of water depth. Therefore, in order to obtain the mean flow velocity at the whole section, multi-survey lines are formed by arranging the detectors in the direction of water depth for scanning measurement.

4. Flow Measurement System

According to how to obtain the mean flow velocity at the whole section of water channel, the following 4 methods are available. These methods are selected properly depending on the plant conditions.

1) A method which measures actually the flow velocity distribution at the whole section by multi-survey lines (*Fig. 13* (a))

The flow velocity distribution in the direction of water depth is obtained from scanning measurement with multi-survey lines. Flow rate is obtained by integrating it in the entirety of water depth. Controls of arithmetic operation, generation of scan signals, procedure to be taken for survey lines which no longer sink under the water when water level is low, and so on, are processed at high speed by a microcomputer.

Type PRM arithmetic unit of microcomputer is fit for arithmetic operation control of such a small-sized system, and it is being used positively for various measurements and controls not only for open channels.

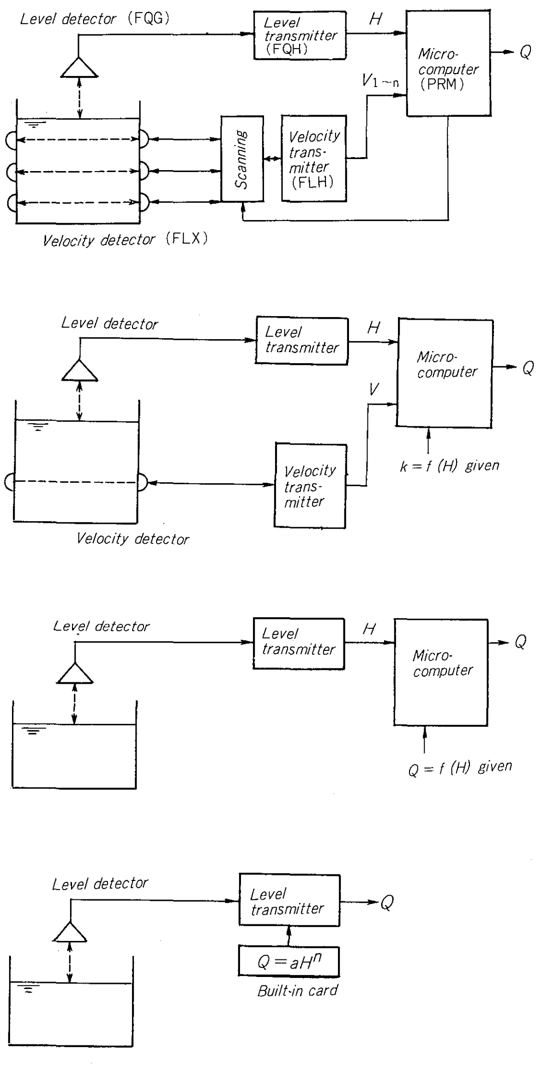


Fig. 13 Flowmeasurement systems of open channels

2) A method which compensates the flow velocity value of one survey line according to water level (*Fig. 13* (b))

To a plant where flow velocity distribution in the direction of water depth is being pre-known as a function of water level (H), this system is applicable. The mean flow velocity value V at the whole section is calculated by multiplying the flow velocity value measured on the fixed survey line, by correction factor, $k = f(H)$. Flow rate is obtained by multiplying the obtained mean flow velocity value by sectional area. In a water channel with little variation in water level, sufficient accuracy can be assured.

3) A method which makes arithmetic operation only with water level (*Fig. 13* (c))

To plant where flow rate is given as a function of only water level (H), this method is applicable.

The applicable condition is that there is no effect of back water from downstream side, and in a water channel where a certain hydraulics formula is already being learnt.

For example, in a water channel where Manning's formula is applicable, the mean flow velocity, V is expressed as follows;

$$V = \frac{1}{n} \cdot R^{2/3} \cdot I^{1/2}$$

Where; n : Coefficient of the roughness of walls
R : Hydraulic mean depth = A/P
A : Sectional area of flowing water
I : Gradient
P : Watted perimeter

Therefore, flow rate may be calculated by multiplying V by sectional area.

4) Water channel for which formula $Q = aH^n$ can be applied (*Fig. 13* (d))

This is a special case of 3) above. This is such that makes arithmetic operation of flow rate with a linearizer circuit incorporated in the transmitter circuit of level meter (FQH), and it is a system which costs least.

The linearizer can make 8-line approximation at the range of 1.5 to 2.5 of n and is applicable even to the weir and flume methods.

Fig. 14 shows an installation aspect of detectors of the velocity meter and the level meter in the water intake channel in a water purification plant.

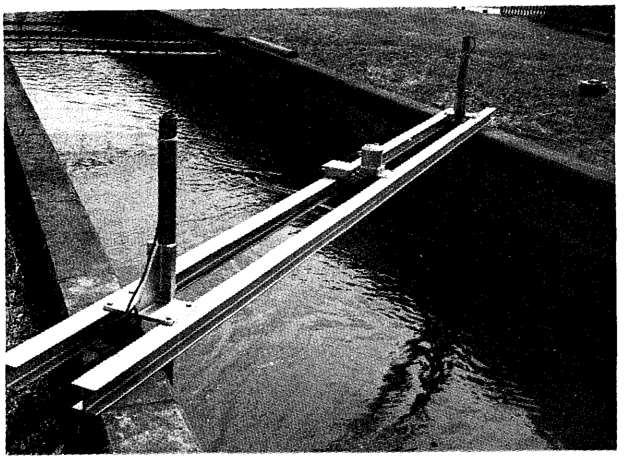


Fig. 14 Installation aspect of ultrasonic detectors for an open channel

VI. CONCLUSION

The recent technique of ultrasonic flowmeter has thus been introduced above.

Hereafter, we'll pay a great efforts for flow measurement in shorter upward straight pipe length and of special flow velocity distribution with a dynamic analysis simulation by the aid of computer, and further expanding the application range of our ultrasonic flowmeters for example, in small-bore pipes and high temperature fluids, and these we will present, when we are ready.