CHARACTERISTICS OF SOUND PRESSURE DISTRIBUTION ON ULTRASONIC DOPPLER METHOD

Sanehiro Wada*, Hiroshige Kikura*, Yoshikazu Koike**, Masanori Aritomi* and Michitsugu Mori***

* Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology,
2-12-1 Ohokayama, Meguro-ku, Tokyo, 152-8550 Japan, e-mail: sane@2phase.nr.titech.ac.jp
, ** Shibaura Institute of Technology, 3-9-14 Shibaura, Minato-ku, Tokyo, 108-8548, Japan,
e-mail: koikey@sic.shibaura-it.ac.jp
*** Tokyo Electric Power Company, 4-1 Egasaki-cho, Tsurumi-ku, Yokohama, 230-8510 Japan,
e-mail: michitsugu.mori@tepco.co.jp

ABSTRACT

Ultrasonic Doppler method (UDM) for a flow metering system has been developed. The method has the capability to obtain instantaneous velocity profiles along the ultrasonic beam. Our purpose is to apply UDM to a flow rate measurement of a circular pipe flow. The principle of the flow measurement method is based on the integration of an instantaneous velocity profile over a pipe diameter. Hence, the accuracy of the flow rate directly depends on the accuracy of velocity profiles measured by UDM. Reflection, diffraction and inflection of ultrasound occur at the boundary of two materials, which have different acoustic impedance. And the transmission coefficient depends on the incident angle of ultrasonic beam, the difference between their acoustic impedance, the thickness of the pipe wall, and the basic frequency of the ultrasound. In this paper, a sound pressure distribution through a metallic plate at each incident angle has been investigated, and considering the results a precise flow rate could be measured when the difference of the acoustic impedance is large and the wall thickness is not same order of the wavelength.

Keywords: sound pressure distribution, transmission of ultrasound, ultrasonic Doppler method, velocity profiles, and metallic pipe wall

INTRODUCTION

As a new flow metering system in a circular pipe, ultrasonic Doppler method has been developed [1][2]. This method has a capability of measuring the instantaneous velocity profile in a pipe over a diameter directly, so it is expected to improve the flow metering performance to be applicable for a transient flow measurement. In order to establish the technique and investigate its absolute accuracy, the comparison among experimental results has been performed at the National Institute of Science and Technology (NIST) flow standards located in Gaithersburg, MD, USA [3]. These results showed that the difference between the averaged ultrasonic Doppler method values and NIST gravimetric measurement were about 0.18%.

The laboratory experiments appeared that for fully developed flow condition an accurate measurement of flow rate was achievable using only a single measuring line, and additionally, for non developed flow which is located just below the bend pipe the multilines method was successfully applied and the errors were less than 1% [4]. However, the results of that the velocity profiles in both near region from the metallic pipe wall were disturbed using nylon powder as ultrasonic reflectors also have been reported. Therefore, when this method applies to a metallic pipe increased the diameter or the thickness, there is a possibility to decrease the precision of a flow rate measurement. This is because that an echo reflected from a boundary of a pipe wall and resonated especially in a metallic pipe wall is very strong. Additionally, an ultrasound through a large metallic pipe might be attenuated, so that the signal-to-noise ratio of detected echo is reduced.

The available ways to overcome these challenges are to consider the effects of a material and thickness of a pipe, a ultrasonic frequency, and an incident angle to a transmission coefficient. The experimental results showed that when a metallic pipe wall is one half-wave length of ultrasound, the velocity profiles and the flow rate would give the most promising accuracy [5].

Therefore, we described about the effects of an incident angle in this paper, when the difference of the acoustic impedance is large and the wall thickness is not same order of the wavelength. A sound pressure distribution through a carbon steel plate at each incident angle has been investigated. And then considering the results, precisions of velocity profiles and flow rates have been estimated.

SOUND PRESSURE DISTRIBUTION

As the container material of the pipe in power plants and industrial plants is a metallic, the transmission of the ultrasonic beam through the metallic wall is important. The propagation and transmission of ultrasound wave follow the common optical law. Reflection, diffraction, inflection and so on occur at the boundary of two materials that have different acoustic impedance. And in solids, both of a longitudinal and a shear wave, which refractions are different, are generated. Table 1 shows the critical angles of both a longitudinal and a shear wave in carbon steel from water.

Table 1 Critical angle of a longitudinal and a shear waves in plexiglass and carbon steel from water

	US velocity [m/s]		Critical angle [deg.]	
	Long.	Shear	Long.	Shear
Water	1,480	-	-	-
Plexiglas	2,350	1,460	39.0	-
Carbon steel	5,950	3,240	14.4	27.2

Experimental setup and method

Fig.1 is the schematic diagram of the measuring a sound pressure distribution, which consists of a transmitting and receiving system of ultrasound, and a test section. Fig.2 shows the photographs of the test section. Pulse ultrasound is transmitted from a transducer connected to X-3 PS-i model Ultrasonic Velocity Profile monitor (Met Flow AG). The beam diameter and the basic frequency are 10 mm and 2 MHz respectively. And then, the pulse is received using a ultrasonic hydrophone connected to a digital oscilloscope (LeCroy: C574AL). The effective and outer diameters of the hydrophone are 0.5 mm and 1.4 mm respectively, and since the hydrophone is placed on a XYZ stage, this system can scan the detail sound pressure filed.

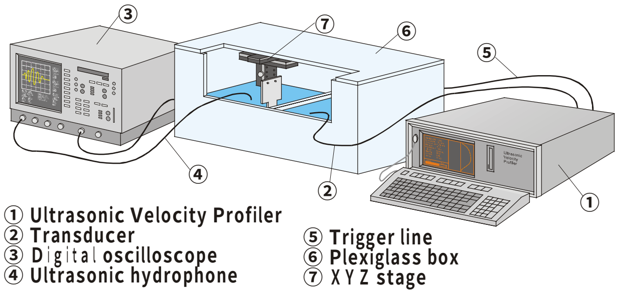
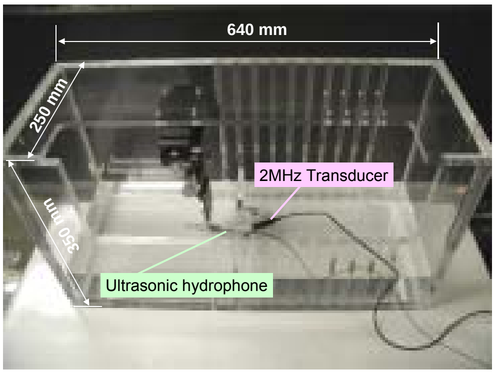


Fig.1 Experimental setup for measuring ultrasound pressure distribution



(a) Water box

(b) Ultrasonic hydrophne (c) Transducer

Fig.2 Phtographs of the test section

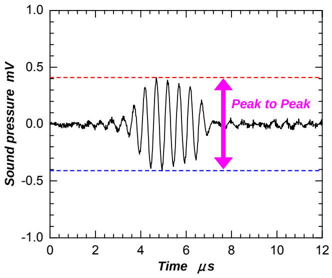


Fig.3 A typical example to calculate a sound pressure

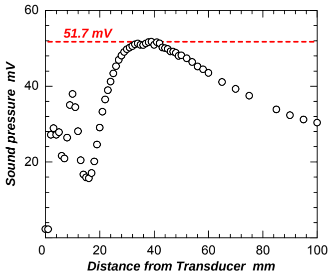


Fig.4 Sound pressure distribution along a center line of a beam without plates

As a metallic plate, carbon steel (SS400) is applied and the thickness is 10 mm. To estimate the effect of an incident angle, the transducer is set up from 5 to 28 degrees, and the hydrophone is traversed along the plate keeping 10 mm from the plate surface.

A transmitted pulse ultrasound from the transducer is detected like Fig.3 by the hydrophone. In this study, a sound pressure of this signal is calculated adopting the peak to peak value. And to difine a transmission coefficient of ultrasound through a metallic plate, the value of the peak to peak is nomalized by a maximal value of a transmissted beam. Fig.4 shows an experimental result of a sound pressure distribution along a center line of the ultrasonic beam without plates.We emploied the maximal value of the sound pressure, 51.7 mV for normalizing.

Results and discussion

The transmission coefficients at each incident angle are plotted against the distance from the edge of the transducer in Fig.5. At 5 and 10 degrees, some maximal peaks are appeared because of the pulses reflecting in the plate and the existence of the both longitudinal and shear waves in the plate. On the other hand, at from 15 to 20 degrees, one strong and narrow peak is formed. Considering the longitudinal ciritical angle is 14.4 degrees (Table 1), this strong and narrow peak is attributed to the shear wave. At 25 and 28 degrees, the peak width becomes broader as increasing the angle due to the beam width on the scanning line increases.

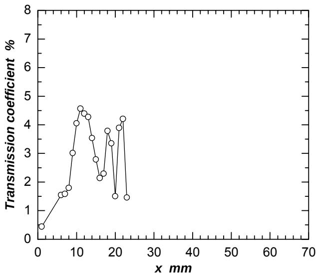
Fig.6 shows the maximum values of the transmission coefficients at each incident angle in Fig.5. It can be seen that at small angle, around 5 degrees, the coefficient has a maximal peak owing to the longitudinal wave, and additionally at around 18 degrees, another maximal peak which is higher than at 5 degrees is expressed due to the shear wave.

VELOCITY PROFILES AND FLOW RATES

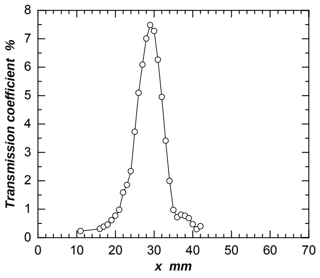
Experimental apparatus and method

Considering the results described above, velocity profiles and flow rates have been measured using UDM. The experimental apparatus consists of a water circulation system, a test section and a measurement system. Fig.7 is the schematic diagram of this apparatus, which was designed and built in to emphasize on the formation of fully developed turbulent pipe flow in both downward and upward directions. In this study, single-phase turbulent pipe flow in upward direction was investigated. Water is circulated by a centrifugal pump from the storage tank into the pipe. The vertical pipe is made of plexiglass, which total length, inner diameter and wall thickness were 6 m, 50 mm and 5 mm, respectively. The flow rate is regulated by the needle valve and monitored by flow orifices and pressure sensor located upstream of the test section. The measuring point was located at 90D downstream from the pipe inlet. The material of the test section is carbon steel (SS400) and the wall thickness is 5 mm.

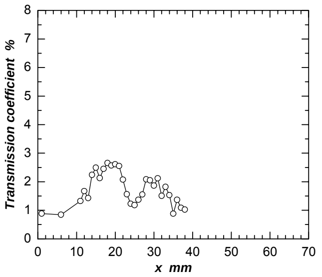
Velocity profiles were collected using UVP monitor at each incident angle. The basic frequency, beam diameter and distance of measurement volumes are 2 MHz, 10mm, and 0.74mm respectively. For reflectors of ultrasound, small bubbles mixing in the pump is suspended in water with the Reynolds number of 24,000.



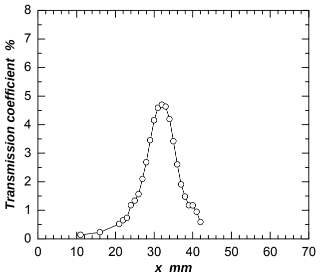
(a) 5 deg.



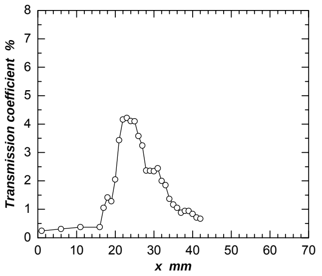
(e) 18 deg.



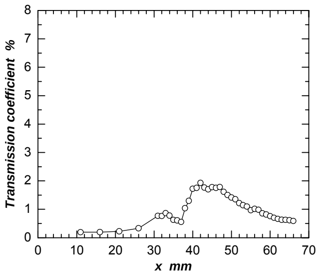
(b) 10 deg.



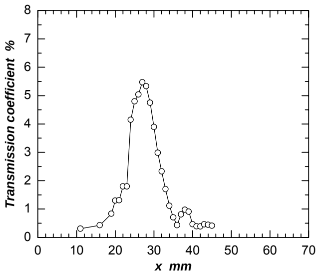
(f) 20 deg.



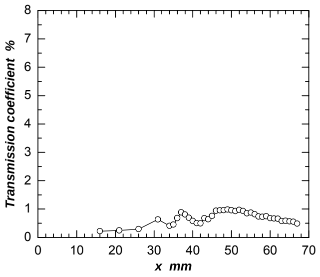
(c) 15 deg.



(g) 25 deg.



(d) 17 deg.



(h) 28 deg.

Fig.5 Transmission coefficients of ultrasound through a carbon steel plate (thickness = 10 mm)

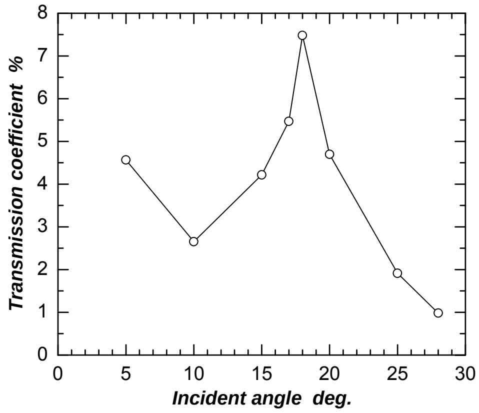


Fig.6 Maximum of transmission coefficients at each incident angle in Fig.5

UDM for a flow rate measurement requires only a single transducer whereby the measurement line goes through the center of a pipe. If a flow is axially symmetric, the flow rate can be obtained accurately by integrating the half of the velocity profile using Eq. 1, which is obtained from the measuring line on the diameter:

$$Q(t) = \frac{\pi}{3}\left\{\frac{R_0^3 - R_1^3}{R_0 - R_1}v_0 + \sum_{i=0}^{n-2}\frac{R_{i+1}^3 - R_{i+2}^3}{R_{i+1} - R_{i+2}}(v_{i+1} - v_i) + R_n^2 v_n\right\} \tag{1}$$

where R_i is the distance from the center of the pipe to the measuring point, and v_i is the velocity of the point.

Results and discussion

The mean velocity profiles at each incident angle are illustrated in Fig.8. The typical data set consists of 1024 instantaneous velocity profiles. As shown in Fig.8, The left half velocity profiles, which are near side from the transducer, is disturbed, and especially at under 15 degrees the disturbed area is larger. Because when the incident angle is small the reflection from the front pipe wall and ringing in the pipe is very strong. Compared Fig.8 with Fig.5, it can be seen that the accuracy of velocity profiles depend on the strength of the transmission coefficient.

As mentioned above, since the left half velocity profile is disturbed, a flow rate is calculated by the right half velocity profile in this paper. The comparison of errors and standard deviations between the measured flow rate using UDM and the volumetric flow rate with respect to the incident angle is illustrated in Fig.9 and Table 2. At less than 15 degrees, the error value increases as increasing the incident angle, due to the longitudinal wave strength becomes weaker. In the opposite, at more than 15 degrees the error decreases, and at around 19 degrees it takes the minimal value, 1.6 %. This is because that the transmission coefficient of the shear wave generated in the pipe wall has the maximum value. Then, over

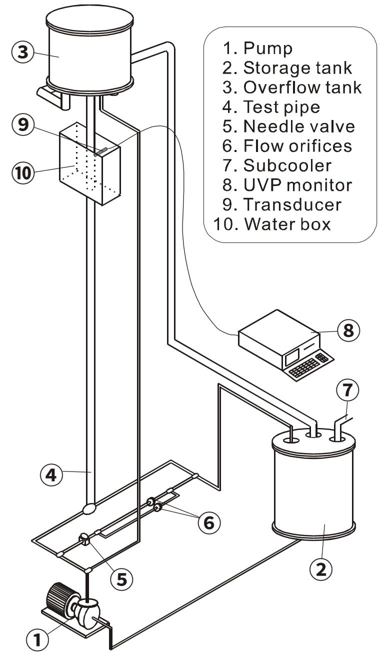
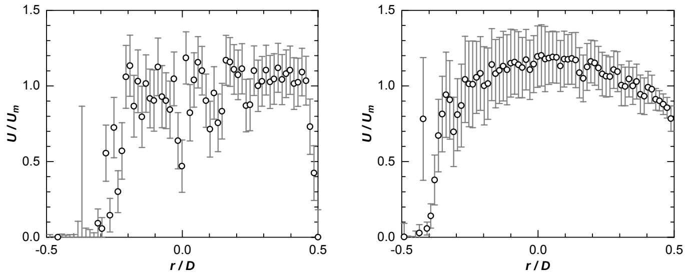
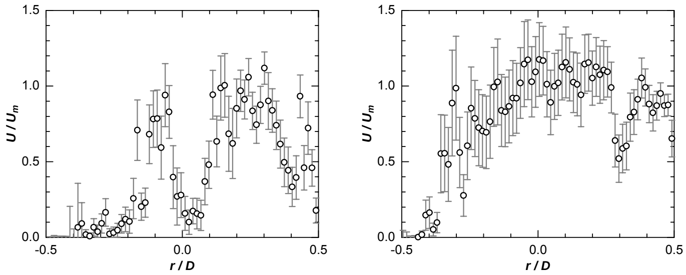


Fig.7 Experimental apparatus for measuring a velocity profile and a flow rate

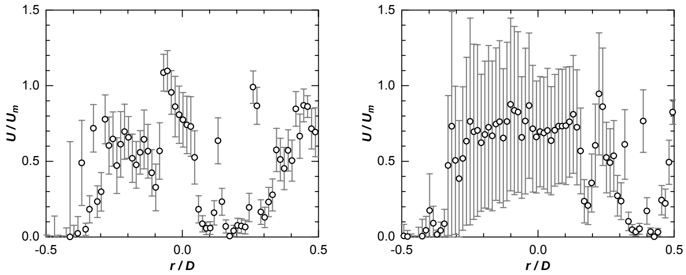
19 degrees the strength of ultrasound occurred by the shear wave in the pipe wall becomes weaker, so that the error of the flow rate increases.



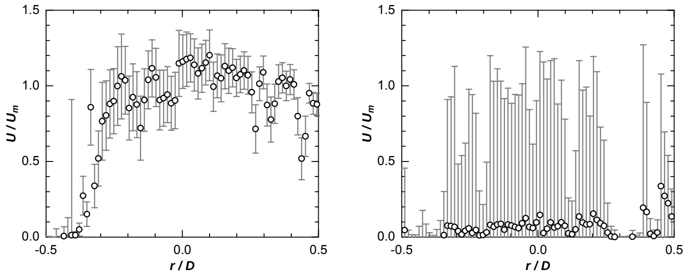
(a) 5 deg. (e) 19 deg.



(b) 10 deg. (f) 20 deg.



(c) 15 deg. (g) 24 deg.



(d) 18 deg. (h) 28 deg.

Fig.8 Mean velocity profiles at each incident angle using carbon steel pipe (Thickness = 5 mm)

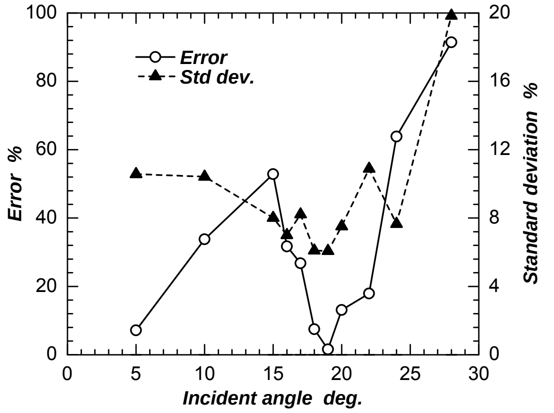


Fig.9 Errors and Standard deviations of flow rate at each incident angle

However, the standard deviation of the flow rate shows the different tendency. At more than 15 degrees, the characteristic between the error and the standard deviation is similar. On the other hand, at less than 15 degrees, as decreasing the incident angle, the standard deviation increases. In this experiment, owing to the pulse repetition frequency of UDM is fixed (2426 Hz), the resolution of the velocity is large in the case of the incident angle is small.

CONCLUDING REMARKS

The effect of the incident angle on measuring velocity profiles and flow rates using ultrasonic Doppler method is investigated in the case of the pipe material is carbon steel. The laboratory experiments appeared that the transmitted ultrasound, which generated by the longitudinal wave in carbon steel, becomes weaker as increasing the angle, and the accuracies of the velocity profile and the flow rate are also reduced.

On the other hand, it is clear that the ultrasound generated by the shear wave has the maximum strength at about 18 degrees, and additionally higher accurate values of the velocity profile and the flow rate are obtained at that angle.

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Table 2 Errors and Standard deviations of the flow rate at each incident angle

Incident angle [deg.]	Error [%]	Std dev. [%]
5	-7.2	10.6
10	-33.8	10.4
15	-52.8	8.0
17	-26.8	8.2
18	-7.5	6.1
19	-1.6	6.1
20	-13.1	7.5
24	-63.8	7.7
28	-91.4	19.8