ACCURACY IMPROVEMENT ON NON-INVASIVE ULTRASONIC-DOPPLER FLOW MEASUREMENT BY UTILZING SHEAR WAVES IN METAL PIPE

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ABSTRACT

In this paper, the essential effect by utilizing shear waves in metal pipes is described in order to improve the accuracy of non-invasive UVP (Ultrasonic-Doppler Velocity Profile) flow measurement along with the transmission/reception efficiency through metal pipe. If the incident angle of ultrasonic transducer from wedge onto metal pipe is set to an angle so as to generate L (longitudinal) waves in metal pipe, SV (shear vertical) waves will be also excited in metal pipe and the ultrasonic transducer will receive two echo signals that correspond to the L wave and the SV wave in metal pipe.

To avoid this double-beam effect, the incident angle of ultrasonic transducer is selected so that the angle of refraction in metal pipe is larger than critical angle of 90 degree for L wave and smaller than that of SV wave, then exciting only SV waves in metal pipe. The authors have got the perspective to be able to achieve high accuracy of ±0.5% for the velocity range of more than 1 m/s ,by optimizing incident angle, reducing multiple reflection and adjusting excitaion frequency of ultrasonic transducer.

Keywords: Shear wave, Incident angle, Multiple reflection, Acoustic noise, Accuracy, Efficiency

1. INTRODUCTION

Recently, UVP method has been often reported as a flow mapping technology. Some papers have also shown the performance of UVP flow meter aimed at industrial use, succeeding in highly accurate flow rate measurement mainly as an invasive type flow meter, that is, a flow meter with wetted transducers [1][2]. However, it is the authors' understanding that the study of UVP method as non-invasive flow metering has not been performed in detail so far. At this time, the fundamental investigation was performed on acoustic propagation through metal/plastic pipes in order to develop non-invasive type UVP flow meter, and it has been recognized that there are various kinds of acoustic interference waves, of which the influence is remarkable especially for metal pipes.

In this paper, the essential effect by utilizing shear waves in metal pipes is described so as to improve the accuracy of non-invasive UVP flow measurement along with the transmission/reception efficiency through metal pipes.

2. CONSIDERATION ON ACOUSTIC NOISES

UVP method receives ultrasonic echo signals reflected by bubbles and/or particles in measured liquid, and calculates velocity profiles by measuring and connecting the Doppler shift frequencies in all channels of the echo signals. Unlike ultrasonic flow meter utilizing transit time method, the transmission of ultrasounds and reception of echo signals are performed by the same transducer.

For highly accurate measurement, it is essential to reduce acoustic interference, which is mainly induced by non-invasive measurement. The would-be acoustic interference is divided into 3 categories as below:

1) Double beam effect:
   L (longitudinal) wave and SV (shear vertical) wave are generated in pipes as fundamental waves in case of non-invasive measurement.
2) Multiple reflection:
   Acoustic interference waves are excited at the interface between two mediums with different acoustic impedances. The authors especially raise multiple reflection in metal pipes.
3) Dispersion effect:
   Lamb waves are generated due to finite pipe thickness, causing split beams in different modes in pipes and then producing frequency characteristics of accuracy.

In this paper, the influence of categories 1) and 2) is described along with their countermeasures. As for dispersion effect, it is reported by the authors' other paper in detail, and only the test data on accuracy are introduced.

3. DOUBLE BEAM EFFECT

3-1. MECHANISM OF DOUBLE BEAM EFFECT

Generally speaking, there are three kinds of acoustic propagation modes in a solid medium with infinite dimensions, L (longitudinal) wave, SH (shear horizontal) wave and SV (shear vertical) wave. L wave is a wave that moves in parallel to particle displacement, and shear waves such as SH and SV waves are ones that move normal to particle displacement.

The sound velocity of L wave is approximately twice larger than that of shear waves in general.

When ultrasounds propagate from medium-1 to medium-2, angle of refraction in medium-2 is determined by the two sound velocities and incident angle into medium-2, yielding to the Snell's law. Therefore, the maximum value of incident angle is limited to the one calculated by the following equation:

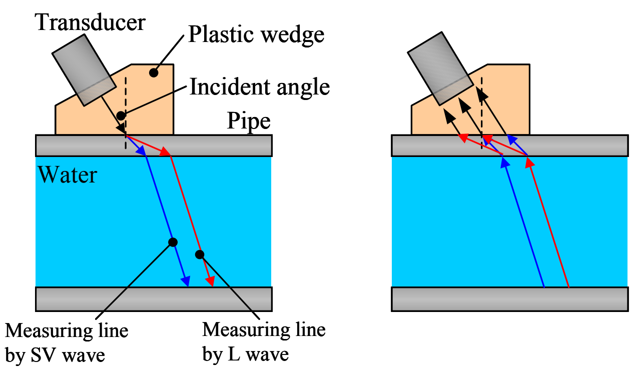
$$\theta_c = \sin^{-1}\left(\frac{c_1}{c_2}\right) \qquad (c_1 < c_2) \qquad (1)$$

where c_1: sound velocity in medium-1, c_2: sound velocity in medium-2 .

If incident angle of ultrasonic transducer from wedge onto pipe is set to an angle so as to generate L waves in the pipe, SV waves will be also excited in the pipe as shown in Fig-1(a), and the ultrasonic transducer will receive two echo signals that correspond to the L wave and the SV wave in the pipe as shown in Fig-1(b).

The echo signals include the same velocity profile information, though they are superposed on each other with different transit time in the pipe.

Therefore the measured velocity profile will be erroneous without measures against this double-beam effect as shown in Fig-2. This effect is remarkable for metal pipes, and is inversely proportional to the inside diameter.



(a) Transmission process (b)Reception process

Fig-1: Acoustic Propagation below Critical Angle of L (Longitudinal) Wave (Double beam effect)

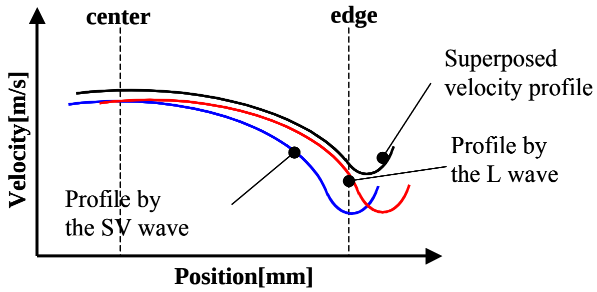


Fig.2: Velocity Profile by Double Beam Effect

For example, the critical angles in SS (stainless steel) pipe are calculated as 28.1degree for L wave and 61.7 degree for SV wave by the Eq. (1), since sound velocities are 5790 m/s for L wave in SS, 3100 m/s for SV wave in SS, and 2730 m/s for L wave in the plastic wedge

When calculating these critical angles at the interface between water and SS pipe, they are 14.9 and 28.8 degree in water for L wave and SV wave in the pipe respectively.

3-2. COUNTERMEASURES AND SIDE EFFECT

(1) IMPROVEMENT OF WAVEFORM

As mentioned above, two kinds of ultrasonic waves will be excited in the pipe if the incident angle is lower than the critical angle for L wave in the pipe. It is considered that the transmitted waveforms from the pipe into liquid would be superposed to each other by this double beam effect. The relation between the incident angle of ultrasonic transducer and the transmitted waveform was experimentally investigated by using the setup as shown in Fig-3.

An ultrasonic transducer with resonance frequency of 2 MHz and diameter of φ13mm was used as the transmitter, and a hydrophone was used as the receiver. These were set into a water tank so as to be in parallel to each other, locating the circular disc that can be tilted between them.

The transducer can widely transmit ultrasounds in the frequency region of 1.5 to 2.5 MHz because of low-Q. The transducer was excited by sinusoidal 4-pulse waves with 2 MHz. The hydrophone has a wide measurable range from 0.5 to 5 MHz, and was connected to the oscilloscope with FFT (fast Fourier transform) function.

The plates were PVC and SS ones 6mm thick.

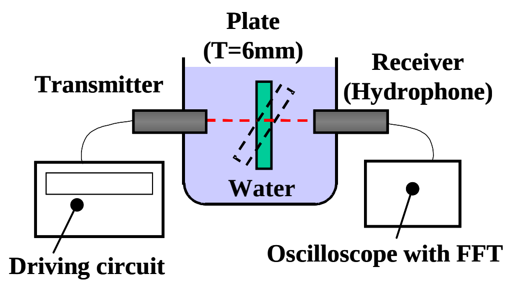
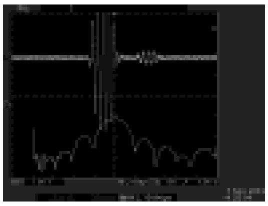
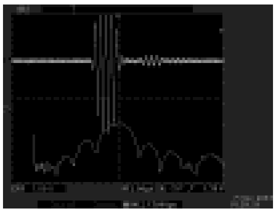
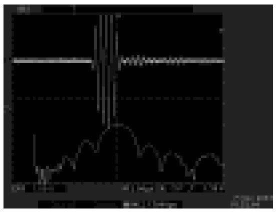
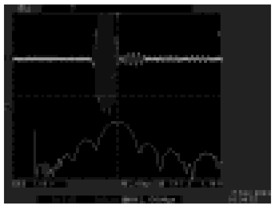
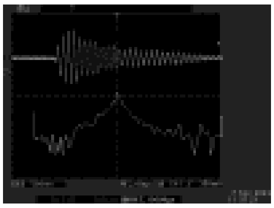
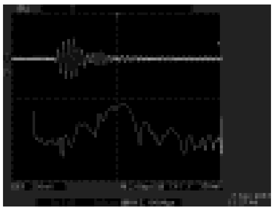
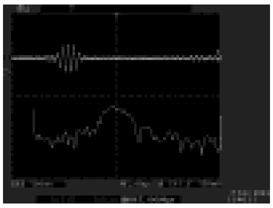
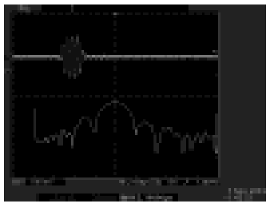


Fig-3: Setup for Investigation of Waveforms

Table-1: Transmitted Waveforms through PVC/SS Plates

	Tilted angle of plate (equal to the incident angle against the plate)			
	0 deg	8 deg	16 deg	23 deg
PVC plate				
SS plate				

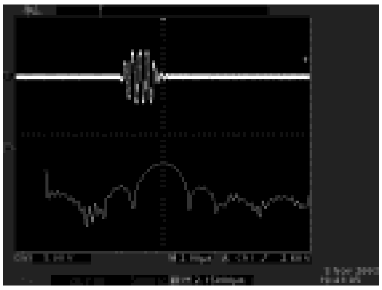


Fig-4: Reference Waveform without Plate

Table-1 shows the test results of transmitted waveforms through PVC/SS plates by changing the tilted angles of the plate. In this table, upper waveforms are ones detected by the hydrophone and lower curves are their frequency spectrums analyzed by the FFT.

Fig-4 shows the reference waveform and spectrum without the plate. In case of PVC plate, the transmitted waveforms were similar to the reference one, and the central frequencies of the spectrums remained at ca. 2 MHz, independent of the tilted angles.

The sound velocity of SV wave in PVC is lower than that of water. Therefore the critical angle does not exist for SV wave, because of not satisfying the condition for Eq. (1). On the other hand, the critical angle is driven to 33.3 degree for L wave, therefore only L waves exist in PVC plate, and there is no double beam effect.

In case of SS plate, the critical angle is calculated as 14.4 degree for L wave. The transmitted waveforms of the tilted angle 0 or 8 degree were distorted compared to the reference waveform. Especially, it was confirmed that resonance phenomenon is occurring at 0 degree. In the spectrums, the central frequencies shift to lower frequency region than 2 MHz.

When the tilted angles were set to 16 or 23 degree of more than the critical angle for L wave, the waveforms were similar to the reference one, and also the spectrums remained almost the same as the reference one.

The double-beam effect was confirmed directly by investigating the transmitted waveforms and spectrums of ultrasounds penetrated though metal/plastic pipes.

(2) IMPROVEMENT OF TRANSMISSION INTENSITY

Furthermore, the relation between transmission intensity through SS plate into water and refraction angle in water (equivalent to incident angle) was investigated by using the same setup as shown in Fig-3. Fig-5 shows the result, in which the vertical scale indicates the ratio of acoustic pressures measured by the hydrophone with/without the SS plate.

Based on this test result, the refraction angle in water has been set to 23.5 degree for the detector of non-invasive UVP flow meter, taking into account the followings:

1) The incident angle of ultrasonic transducer onto pipe should be larger than the critical angle for L wave in metal pipe, and smaller than that of SV wave to avoid the double beam effect.
2) The incident angle of ultrasonic transducer onto pipe should be set to near the peak of transmission intensity into water

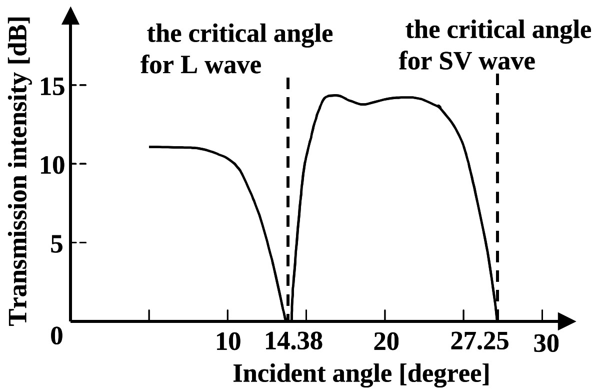


Fig 5: Transmission Intensity vs. Incident Angle

If only shear waves are utilized in metal pipes, the transmission intensity into liquid will be also improved, because penetration rate of ultrasounds will increase at the interface between metals and liquid. However, it will cause a side effect in the next.

(3) LIMITATION OF MAXIMUM VELOCITY

If utilizing SV wave in metal pipes, the maximum velocity of UVP method will be limited to lower value than that in case of L wave. The Doppler shift f_D is expressed by

$$f_D = \left(\frac{2V}{C_f}\sin\alpha\right) f_0 \qquad (2)$$

where V: velocity, C_f: sound velocity of liquid, α: refraction angle in liquid, f_0: basic excitation frequency of ultrasonic transducer.

Because pulse repetition frequency (PRF) corresponds to a frequency of the sampling theorem, the PRF needs to be set to more than twice the maximum Doppler shift.
Besides, PRF needs to be adjusted so that twice of transit time from transducer to opposite wall is smaller than that of PRF. Therefore, PRF is restricted by the following:

$$2f_D \leqq \mathrm{PRF} \leqq 1/(\text{twice of transit time}) \qquad (3)$$

Then, the maximum velocity V_{max} is given by

$$V_{\max} \le \frac{C_f^{\,2}}{8Df_0 \tan\alpha} \qquad (4)$$

where D: inside pipe diameter.

Table-2 shows the comparison between refraction angle in water of 8 and 23.5 degree. The maximum velocity is limited to one-third or so by the adoption of only SV waves in metal pipes. However, it is possible to incrase the maximum velocity by lowering resonance frequency of ultrasonic transducer.

Table-2: Comparison between Different Refraction Angles

Refraction angle in water	8deg	23.5deg
Inside diameter	100 mm	
Frequency	2 MHz	
Propagation mode	L wave + SV wave	SV wave
Maximum velocity	19.9 m/s	6.4 m/s

4. MULTIPLE REFLECTION

As for acoustic interference, there would be various types such as below (refer to Fig-6):
a) Multiple reflection in pipe wall
b) Multiple reflection between inside wall surfaces
c) Combination of a) and b)

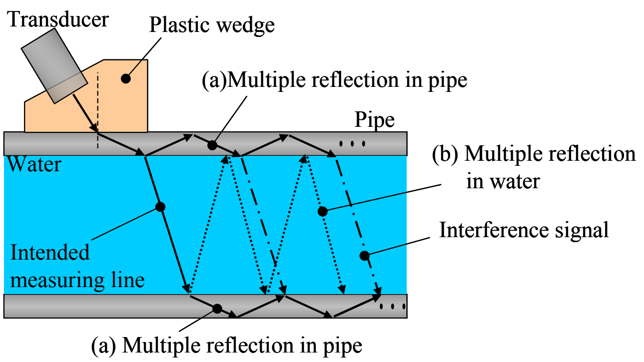


Fig-6: Multiple Reflection

It is of crucial importance for non-invasive UVP measurement to reduce the above-mentioned interference that might cause the similar effects same as double beam effect. That is because many of transmitted ultrasounds come back to the transducer after scattered by reflectors in liquid or reflected by piping devices.

To avoid the interference, acoustic absorber made of material with high acoustic impedance, such as rubber with tungsten particles, should be installed in front of transducer so as to absorb the interference waves of type a), and then type c). Fig.7 shows the detector's configuration for non-invasive UVP flow meter.

On this matter, the authors think that more detailed and comprehensive studies will be needed in the future.

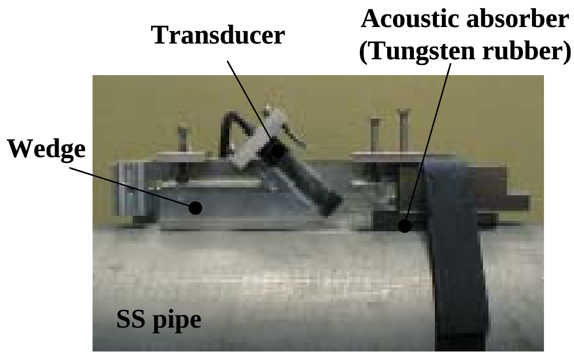


Fig.7: Configuration of Detector

5. EVALUATION OF ACCURACY

5-1. EXPERIMENTAL SETUP

Based on the fundamental analysis and tests as mentioned above, the accuracy tests were performed by using the test facility as shown in Fig-8.

The tests were done for PVC pipe and SS pipe with nominal diameter of 100 mm and thickness of 4.8 mm and 5.9 mm respectively. The detector was installed on the pipe surface by 10D downstream from a flow conditioner. The accuracy evaluation was performed by so-called the comparison method with an EMF (electromagnetic flow meter). The EMF was calibrated within ±0/1% by gravimetric method. The liquid was water that contains air bubbles as velocity field tracers. Air was injected into water on the suction side of upstream pump, and was broken into micro bubbles by the pump.

In case of PVC piping, the acoustic absorber was not used because the effect of the acoustic interference is small.

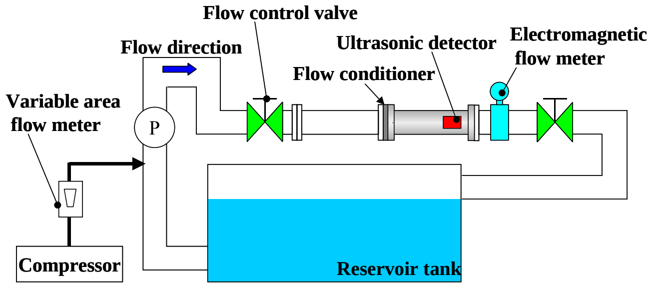


Fig-8: Test Facility for Accuracy Evaluation

5-2. EFFECT OF SHEAR WAVES

In order to confirm the effect of shear waves, the accuracy tests were performed, using two types of wedges made of Plexiglas to cause two different refraction angles in water of 8 degree and 23degree, and comparing those flow profiles. As to the excitation frequency of ultrasonic transducer, it was set to 2 MHz that corresponds to the resonance frequency of piezoelectric device.

Table-3 shows the velocity profiles and accuracy at that time.

As for the velocity profiles, it was confirmed that those of 23 degree are smoother than those of 8 degree for both cases of PVC pipe and SS pipe.

As for the accuracy, it was confirmed that the accuracy in case of 8 degree is less than 7 % of rate for PVC pipe and ca. 20% of rate for SS pipe. On the contrary, it was confirmed that the accuracy in case of 23 degree is ca. 2% of rate for PVC pipe and ca. 4% of rate for SS pipe.

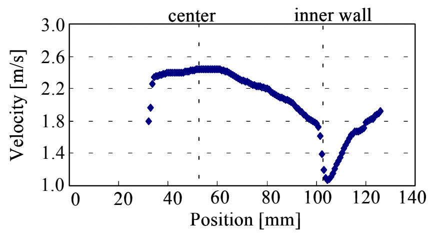
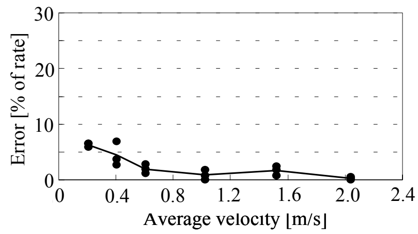
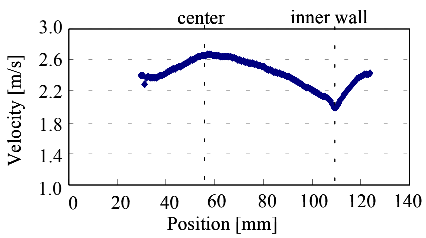
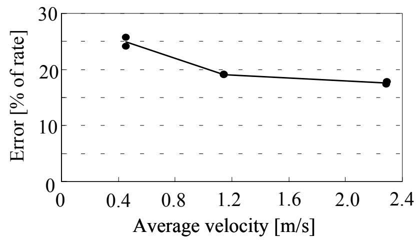
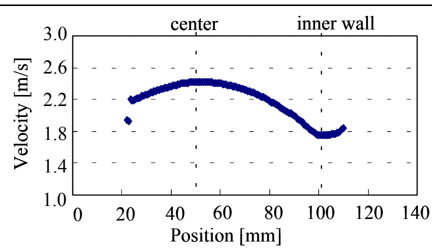
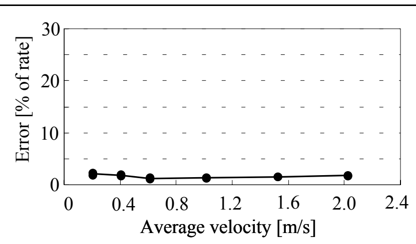
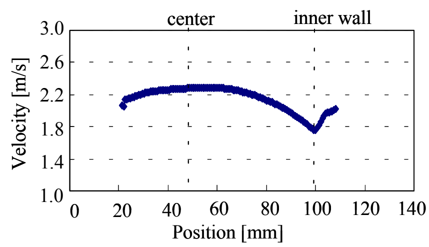
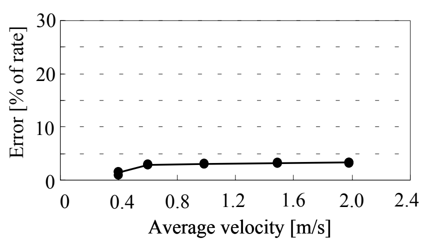
From these results, it was concluded that the adoption of only SV waves in metal pipes has take advantage over that of L waves and then SV waves in addition.

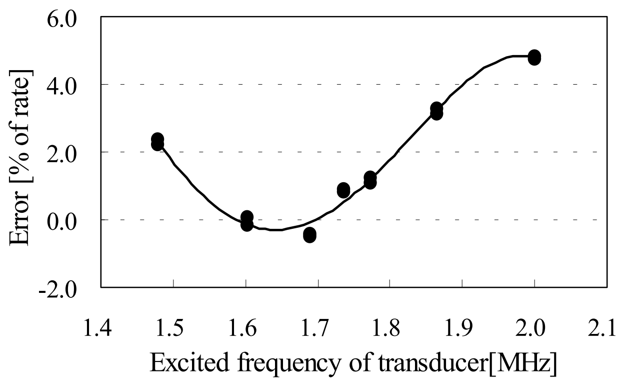
5-3. FREQUENCY CHARACTERISTICS

Additionally, the authors have got the fact that the excitation frequency effects on the accuracy of non-invasive UVP measurement. The mechanism and analysis is shown in authors' other paper in detail. Therefore, in this paper, were shown the test results of the frequency characteristics and the effect after tuning the excitation frequency.

Fig-9 shows one example of the frequency characteristics. Fig-10(a) and (b) show the test results on the accuracy applied to SS pipe and CS pipe.

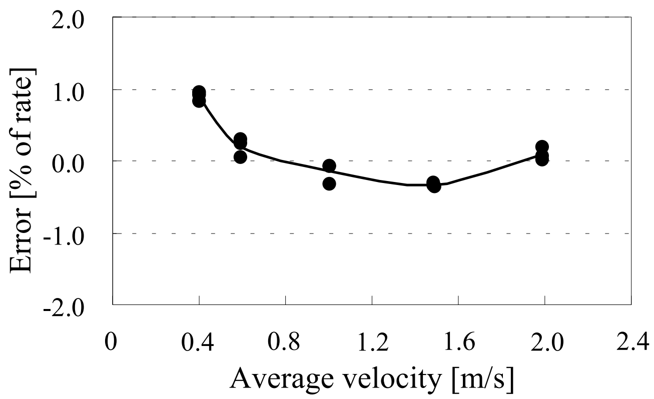
Table-3: Comparison of Velocity Profile and Accuracy

Incident angle	Pipe material	Velocity profile	Accuracy
8 deg	PVC		
	SS		
23 deg	PVC		
	SS		



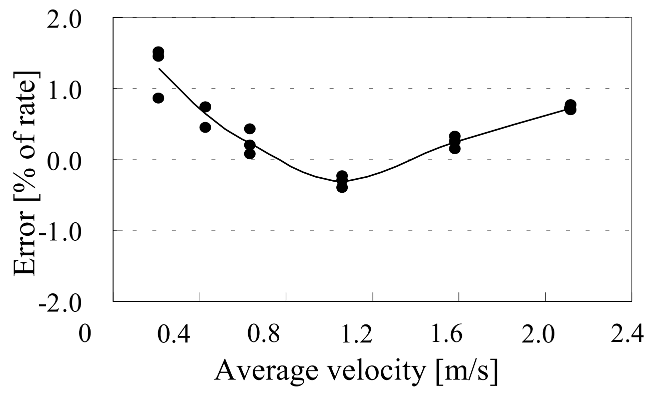
Inside diameter/thickness: 102.1 mm/5.9 mm
Resonance frequency of transducer: 2 MHz
Average velocity: ca. 2 m/s

Fig-9: Frequency Charactristics for SS Pipe



Inside diameter/thickness: 102.1 mm/5.9 mm
Excitation frequency: 1.6 MHz

Fig.10(a): Accuracy in Case of SS Pipe



Inside diameter/thickness: 106.0 mm/4.39 mm
Excitation frequency: 2.0 MHz

Fig-10(b): Accuracy in Case of Carbon Steel Pipe

6. CONCLUSIONS

The accuracy of non-invasive type UVP flow meter was improved by avoiding double-beam effect and reducing multiple reflection. It was also commented that the accuracy was improved by tuning the excitaion frequency.

The wedge angle of ultrasonic transducer was selected so that incident angle onto metal pipe is larger than the critical angle for L wave in the pipe and smaller than that of SV wave, then exciting only SV waves in the pipe. Furthermore the acoustic absorber was installed in front of ultrasonic transducer for the sake of absorbing the multiple reflection in the pipe.

As a result, it was confirmed that the accuracy would be ±0.5% for the average velocity of 1 to 2m/s even if UVP method is applied to non-invasive flow meseasurement.

7. REFERENCES

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