A study of ultrasonic propagation for flow rate measurement using ultrasonic flowmeter

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The purpose of this study is to measure flow rates with high accuracy by using ultrasound. Experimental study has been conducted on ultrasonic properties which are necessary for the measurement. An automatic measurement system which can measure three-dimensional sound field has been developed. With this system, ultrasonic sound pressure distributions and refraction angles in the water have been measured. According to Snell's principle the ultrasonic transmission property can be obtained on the basis of incidence angle, acoustic impedance, basic frequency of ultrasound, and material and thickness of metallic plate. However this principle can't be applied to certain cases where an ultrasonic incident wave passes through a metallic plate and turns into a longitudinal wave, a shear wave and a Rayleigh wave. Consequently the ultrasonic propagation paths have been investigated experimentally at various angles of incidence. The most suitable incidence angle has been determined from the result of measurements, and flow rates are measured.

Keywords: flow rate measurement, ultrasonic flowmeter, ultrasonic propagation, incidence angle, refraction of ultrasound

1 INTRODUCTION

At present differential pressure type flow meters such as Oriffice, Nozzle and Venturi have been used for industrial piping flow rate measurements from the view point of low cost and global standard. However these methods have a problem of measurement errors which are caused by changes in flow conditions under aging phenomena, for example, surface wear, corrosion and metal deposition inside pipes. To cope with these concerns, time-of-flight (TOF) and Cross-Flow type ultrasonic flow meters, which are strapped onto the outside of a pipe, are being introduced to nuclear power plants in the United States. These methods are easier to install. However, these methods, which require flow profile factors (PFs) determining the theoretical velocity profile, strongly depend on the real flow profiles. Since real velocity profiles in plants are affected by turbulent flow and inner surface wear in the pipe under aging phenomena, PFs can't be determined easily.

On the other hand, as a new flow metering system in a circular pipe, an ultrasonic velocity profile (UVP) method has been developed [1][2]. This method can measure instantaneous velocity profiles in a pipe over a diameter directly, so flow rate is calculated using the integration of the averaging velocity profile [3][4]. In order to establish the technique and investigate its absolute accuracy, experimental results have been compared with flow standard at NIST [5]. These results showed that the difference between the averaged Ultrasonic Doppler Method values and NIST gravimetric measurement is about 0.18%. In addition, even if a bigger turbulent flow is developed, the error is 0.38%. In this case two more ultrasonic measurement lines are used to achieve higher accuracy [4].

In the case of clamp-on type ultrasonic flow meters, acoustic parameters such as ultrasonic pressure and incidence angle have a huge effect on flow metering accuracy [6][7]. According to Snell's principle the ultrasonic transmission property can be obtained on the basis of incidence angle, acoustic impedance, basic frequency of ultrasound, and material and thickness of metallic plate. However this principle can't be applied to certain cases where an ultrasonic incident wave propagated through a metallic plate turns into a longitudinal wave, a shear wave and a Rayleigh wave.

Experimental study was conducted on ultrasonic properties which are necessary to measure flow rates with accuracy. The automatic measurement system which can measure three-dimensional sound field has been developed. By using this system, ultrasonic sound pressure distributions and refraction angle in the water were measured.

Consequently the ultrasonic propagation paths were investigated experimentally at various angles of incidence. The most suitable incidence angle was determined from the result of measurements, and flow rates were measured.

2 ULTRASONIC PROPAGATION PROPERTY

UVP method processes reflected signals from particles in working fluids to measure velocity profiles. In addition ultrasonic refraction angle in pipe

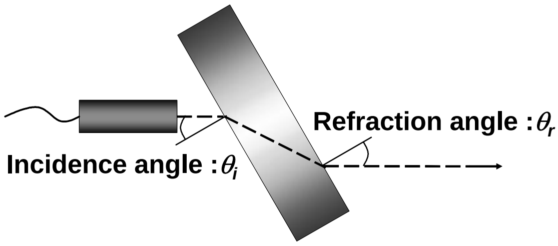


Figure 1: Incidence angle θ_i and refraction angle θ_r

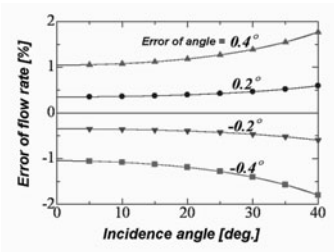


Figure 2: Theoretical error of ultrasonic flow meter when incidence and refraction angles change

is used to calculate axial velocities. There are some concerns about the measurement using UVP. One is signal degradation from particles because of a bigger impedance difference between metallic pipes and working fluids. Another is that errors of ultrasonic incidence angle and refraction angle shown as Figure 1 have a significant effect on flow measurement accuracy. In theory, flow rates calculated from velocity profiles is derived from the followings:

$$Q(t) = \iint V_x(r, \theta_r, t) r dr d\theta \quad (1)$$

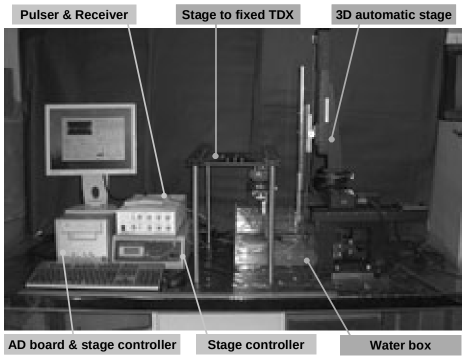
θ_r : refraction angle, V_x : axial direction velocity

r : pipe radius, t : time

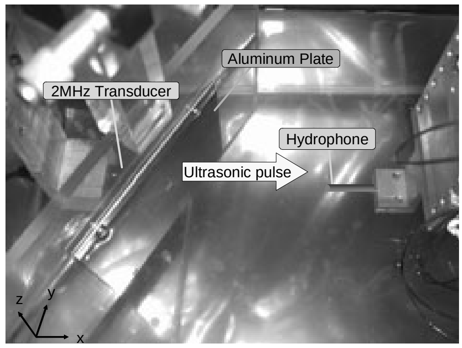
Figure 2 shows the flow measurement errors caused by the errors of incidence and refraction angle. In the results, ultrasonic propagation properties through metallic piping need investigations.

2.1 Experimental-setup and method

The schematic diagram of the system for measuring 3D ultrasonic distributions is shown in Figure 3-(a). This system consists of an ultrasonic transmitting and receiving system, and an oscilloscope and a 3D-automatic stage with PC. And the schematic diagram of the measuring area is shown in Figure 3-(b), consisting of a fixed transducer (2MHz, ϕ10), a hydrophone (□1mm) and aluminum plate (thickness = 1.5mm). A hydrophone is movable freely by using the automatic XYZ axis stage, as shown Figure 3-(b). The aluminum plate can rotate horizontally to change incidence angles in a water box (400mm×200mm×200mm; Plexiglas).This test area is filled with filtrate 23degree-water. Ultrasonic pulse, which is emitted from a pulser (Matec; TB-1000, Pulse



(a) Overall view



(b) Measurement tools

Figure 3: Experimental system for measuring ultrasonic pressure distribution

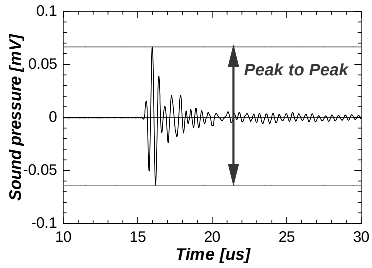


Figure 4: A typical example of sound signal

Width = 1us), penetrates the aluminum plate and is received by the hydrophone. This averaging signal is stored in a computer using AD converter (National Instruments; NI5112, 8bit, 100MHz Sampling).

The test sections are the square of having size of 21mm×21mm, so both x and y axes measuring division is 0.5mm. And the squares locate at 30mm, 70mm 120mm along z axis. Sound pressure is defined as Peak to Peak shown by Figure 4 and sound pressure is calculated from averaging signals.

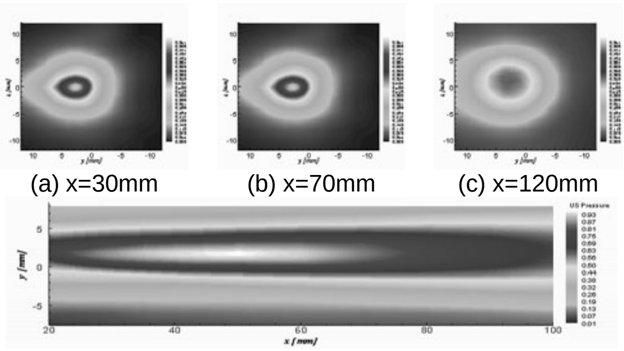
2.2 Results and discussion

Figure 5 shows the ultrasonic sound pressure distribution through an aluminum plate at 29deg. Incidence angle.

Figure 6 shows the ultrasonic intensity, *Peak to Peak,* calculated from received signals. In the case of using a thick plate, *Peak to Peak* attenuates near longitudinal and shear critical angles, 13,3degrees and 29.1degrees respectively. But the values of sound pressure are the largest near the critical angle of shear wave in the case that plate thickness is thick plate. This phenomenon is attributed to leaky wave.

Figure 7 shows the differences between θ_r and θ_i. Larger differences can be seen at the critical angle of longitudinal wave and above the critical angle of shear wave. When the incidence angle is nearly equal to 29degrees, the differences are smaller than the other incidence angles in the case of a thin plate (thickness = 1.5mm).

It can be concluded that the best incidence angle is 29degrees in the case of thin plates to measure flow rates using UVP with high accuracy.



(a) x=30mm (b) x=70mm (c) x=120mm

(d) xy cross section

Figure 5: Sound pressure distributions (θ=29deg. TDX:2MHz, Aluminum plate thickness: 1.5mm)

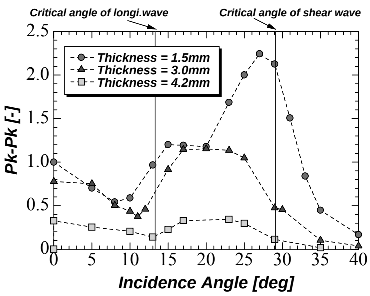


Figure 6: Maximum of transmission coefficients at each incidence angle through a aluminum plate (TDX:2MHz)

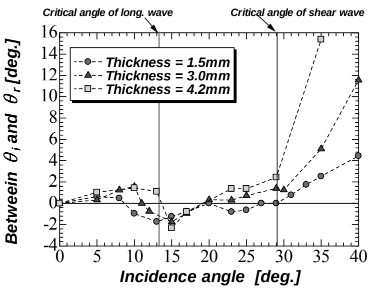


Figure 7: Distances between incidence angle θ_i and refraction angle θ_r. (TDX:2MHz)

3 FLOW RATE USING VELOCITY PROFILES

3.1 Experimental-setup and method

Considering the results described above, velocity profiles and flow rates have been measured using UVP. The experimental apparatus consists of a water circulation system, a test section and a measurement system. Figure 8 is the schematic diagram of this apparatus, which is designed and built to emphasize the formation of fully developed turbulent pipe flow in both downward and upward directions. In this study, single-phase turbulent pipe flow in the upward direction was investigated. Water is circulated by a centrifugal pump from the storage tank into the pipe. The vertical pipe is made of Plexiglas, of which the total length, inner diameter and wall thickness were 2.5m, 50mm and 5mm respectively. Reynolds number is 20000 regulated by the needle valve and monitored by an electro magnetic flowmeter located upstream of the test section. And upstream which arrives at the overflow tank is drained off to the storage tank. Working water is monitored to keep 20±0.5degC by a mercury thermometer. The measuring point is located at 12D from the line entry at the bottom. The material of the test section is aluminum and the wall thickness is 1.5mm. Velocity profiles were collected using UVP (Met-Flow; UVP-X3) at each incidence angle. The basic frequency, beam diameter and distance between to the adjacent measurement points are 2MHz, 10mm, and 0.74mm respectively. Considering acoustic impedance, water used as coupling between a transducer and an aluminum pipe. Nylon particles (WS200P) whose averaging diameter and relative density is 80μm and 1.02 are used as ultrasonic reflectors because its density is nearly equal to density of working water.

Flow rate measurements using UVP require a

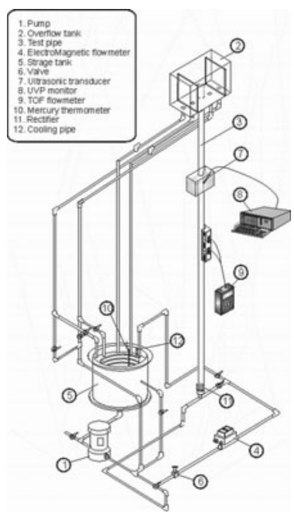


Figure 8: Experiment apparatus for measuring velocity profiles and flow rates (test section: Aluminum; D=50mm, thickness=5.0mm, height≈45D)

velocity profile inside a pipe in the case of axial symmetric flow. And flow rates are calculated by integrating a velocity profile around a pipe axis. This calculation formula is shown as Equation(2). In addition, linear interpolation is applied to distances between each measurement point.

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

where *Ri* is the distance from the center of the pipe to the measuring point, and vi is the velocity of the point.

3.2 Results and discussion

Figure 9 shows mean velocity profiles in aluminum pipe at 4 incidence angles (thickness = 1.5mm) on each incidence angle. These profiles were ensemble averaged using 1024 instantaneous velocity profiles. Noise from metallic wall disturbs velocity profiles near the transducer side. However, this problem is solved when incidence angle is 29degree, which is the best angle as described above. It is observed that velocities of the pipe center vary with each incidence angle as Figure 9. But it is been able to read out the changing pipe center velocity when incidence angle is changed. The result indicates changes of refraction angle. So Figure 10 shows the results of flow rate measurement using velocity profiles of the other side from the transducer and flow rate using the measurement of sound pressure.

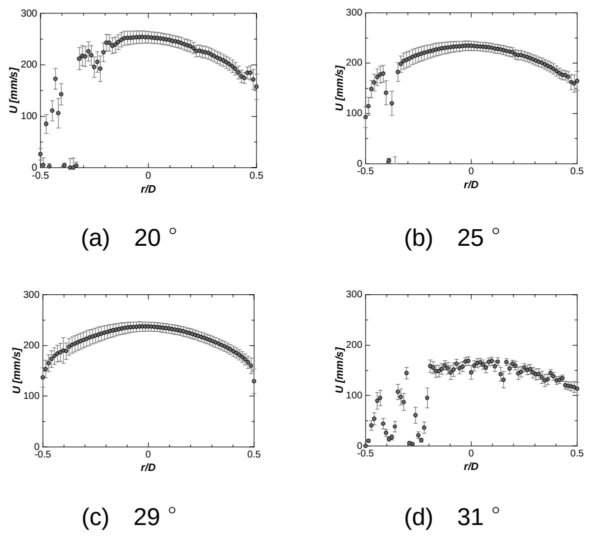


Figure 9: Mean velocity profiles in Aluminum pipes at 4 incidence angles (Pipe Thickness = 1.5 mm, h=12D)

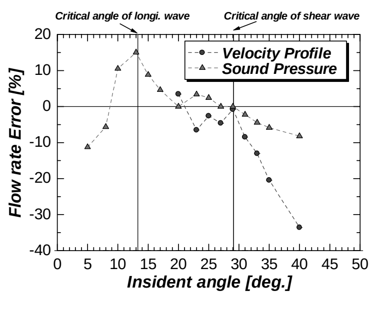


Figure 10: Error of flow rate at each incidence angle

Considering the results described above, ultrasonic flow metering using UVP is high accuracy measurement method, if a better incidence angle is chosen.

4 SUMMARY

Experimental study was conducted on ultrasonic properties which are necessary to measure flow rates with accuracy. The automatic measurement system which can measure three-dimensional sound field has been developed. By using this system, ultrasonic sound pressure distributions and refraction angles in the water were measured. According to Snell's principle the ultrasonic transmission property can be obtained on the basis of incidence angle, acoustic impedance, basic frequency of ultrasound, and material and thickness of metallic plate. However this principle can't be applied to certain cases where an ultrasonic incident wave propagated through a metallic plate turns into a longitudinal wave, a shear wave and a Rayleigh wave. Consequently the ultrasonic propagation paths were investigated experimentally at various angles of incidence. The most suitable incidence angle was determined from the result of measurements, and flow rates were successfully measured with high accuracy.

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