Study of Flow Measurement by Air-coupled Ultrasound

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A non-contact flowrate measurement using the air-coupled ultrasound beam focusing technique is developed and applied to the metal pipe flowrate measurement. Ultrasonic sensors are fixed in the air. Ultrasonic sensors transmit and detect ultrasound through air, and measure the flow rate in the pipe. However, most of ultrasound is refracted and reflected at the boundaries between air and pipe, and detected signals are weak. Especially, it is difficult to apply to the metal pipes. To increase the signal amplitude, we developed focusing ultrasonic sensor that was optimized for the pipe flow measurement. The focusing sensor has a round vibrating surface. And it enables to transmit ultrasound to the pipe effectively by controlling ultrasonic beam. In present study, flowrate measurement by time of flight method is demonstrated in aluminum pipe, and focusing sensor is also available to increase signal to noise ratio for the development of air-coupled ultrasonic velocity profiler. And because the focusing sensor causes the wedge shape measurement line and changes spatial resolution, the verification of measurement line is performed by the finite element method.

Keywords: Air-coupled ultrasound, Non-contact flowmeter, Beam focusing, Time of flight.

1 INTRODUCTION

Ultrasonic flowmeter [1] is widely applied to non-invasive measurement, and the measurable flow range is wider than the pressure difference flowmeter. Besides, the ultrasonic flowmeter can be applied to the high accuracy measurement because of the acoustic technique development and the signal processing [2]. However, the piezo-electric element in the ultrasonic sensor has difficulty in applying the high temperature condition. Especially, in the higher condition than the Curie-temperature, the ultrasonic sensor loses the piezoelectricity, and the desensitization occurs. For example, narrow pipe flowrate measurement of molten glass is required when molten glass is injected to the canister from the glass melter in the vitrification process of high level radio-active liquid waste.

To overcome such limitation, we focused on the air-coupled ultrasound [3]. Sensors are not contacted to the pipe using air-coupled ultrasound, and the air is effective for insulting material to protect the sensors from high temperature conditions [4]. Therefore, development of non-contact ultrasonic velocity profiler (UVP) is our ultimate target. However, in the air-coupled ultrasonic measurement, the amplitude of received signals is decreased, because of the refraction and reflection between the air and pipe. The signal to noise ratio (SNR) is not enough to obtain the Doppler frequency. Therefore, time of flight (TOF) flowmeter by air-coupled ultrasound is developed for the fundamental study of air-coupled UVP system.

For the TOF method, most acoustic energy is reflected at the boundary between air and metal pipe, and the improvement of SNR is required [5]. One of the methods to increase the SNR of receiving signals is to enlarge the cross section of the ultrasonic beam. However, ultrasound transmitted from the edge of the sensor, is refracted at the curve of the pipe on the conventional planar sensors, and beam spreading occurs in the pipe. In order to reduce the refraction to other directions, the focusing sensors that have the cylindrical vibrating surface and transmitted ultrasound are directed to the center of the pipe [6]. The focusing sensor is proposable to transmit the ultrasound to the pipe effectively, however, for air-coupled UVP system, focusing sensors cause the wedge shape beam propagation, and it makes different measurement line from conventional sensors. To verify the measurement line, numerical simulation is performed, and the measurement line is evaluated.

2 TIME OF FLIGHT (TOF) ULTRASONIC FLOWMETER

2.1 Principle

In the conventional TOF ultrasonic flowmeter, two ultrasonic sensors are contacted to the pipe. And the ultrasound is transmitted from one sensor setup in the upstream to the flow and propagates in the fluid. From the difference of TOF, the flowrate can be obtained. Based on the conventional flowrate measurement method, the flowrate measurement method by air-coupled ultrasound is developed. The air-coupled ultrasound propagates in the air and enters to the pipe. Therefore the refraction in the boundary between the air and pipe and the propagation time in air are taken into consideration.

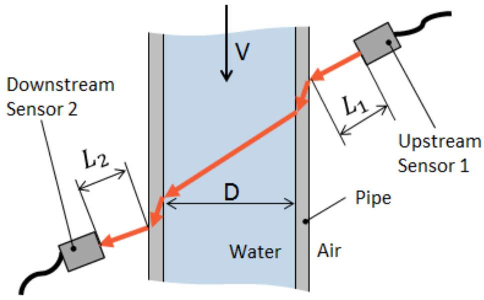


Fig.1 The measurement principle of TOF method in the air-coupled ultrasonic flowmeter.

When wave propagates from the air to water, the incident angle θ and the refracted angle ϕ are related with the speed of sound in water C_w and in the air C_a as

$$\frac{\sin\theta}{\sin\phi} = \frac{C_a}{C_w} \tag{1}$$

The propagation time for the upstream of the flow t_{up} is calculated by using the average velocity of water V, the distance between the surface of the pipe and ultrasonic sensors L_1, L_2 and the diameter of the pipe D as

$$t_{up} = \frac{L_1 + L_2}{C_a} + \frac{D}{\cos\phi(C_w + V\sin\phi)}. \tag{2}$$

The no flowing propagation time $t = 0$ is obtained by substituting $V = 0$ into the Eq. (2). And, the time difference Δt is

$$\Delta t = t_{up} - t_0 = \frac{D}{C_w \cos\phi} - \frac{D}{\cos\phi(C_w + V\sin\phi)} = \frac{V\tan\phi}{C_w + V\sin\phi}. \tag{3}$$

Then, the flowrate Q can be calculated from the average velocity V as

$$Q = \frac{\pi D^2}{4} V = \frac{\pi D^2 C_w \Delta t}{4(\tan\phi - \Delta t \sin\phi)}. \tag{4}$$

To measure the average flow velocity, the speed of sound in water, that in air, the incident angle and time difference are required in Eq. (1) and Eq. (4). And it is cancelled by the difference from the conventional method, that is the effect of propagation time in the air. Thus, the flowrate can be obtained by measuring the TOFs when under the no flowing.

2.2 Prevention of refraction at the pipe

The conventional ultrasonic sensors have planar vibration surfaces, and ultrasound emitted at the edge of the sensors is refracted at the curve of pipe and without reach the other sensor (Fig. 2). It causes the decrease of SNR. Even if the cross section of the sensor is enlarged, the effect of the refraction is increased, that is few improvement on the result of SNR. In order to prevent the refraction at the curve of pipe, focusing sensors are developed. There are vibrating elements facing to the surface of pipe in focusing sensors, therefore, the emitted ultrasound directs to the pipe and the effect of the refraction is decreased (Fig. 2). This focusing sensors are optimized to measure the pipe whose outer diameter is 60 mm, and the distance between the pipe and sensor is 10 mm. Therefore, the focusing sensor has 40 mm radius surface and focusing point is 40 mm from the sensor. It has 20 × 20 mm and radius 40 mm round vibrating surface (Fig. 3).

3 FLOWRATE MEASUMENT BY AIRCOUPLED ULTRASONIC FLOMETER

3.1 Experimental setup

The flowrate measurement in the aluminum pipe is demonstrated, applying focusing sensors. The aluminum is widely used for the industrial pipe and has lower acoustic impedance in the metal. The experimental setup is shown in Fig. 4. This apparatus consists of an electromagnetic

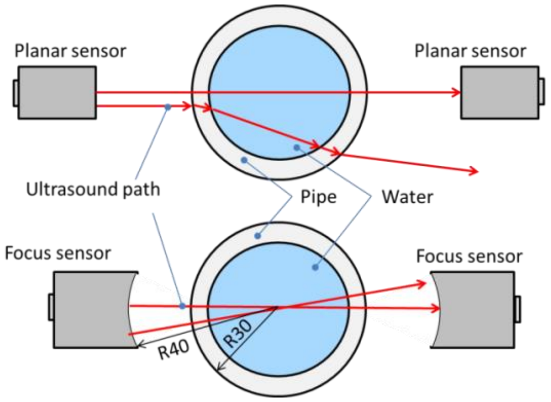


Fig. 2 Ultrasound path using planar sensors and focusing sensors.

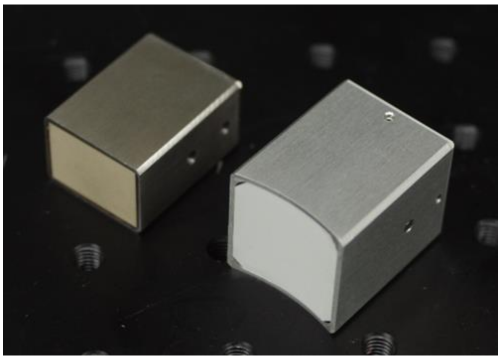
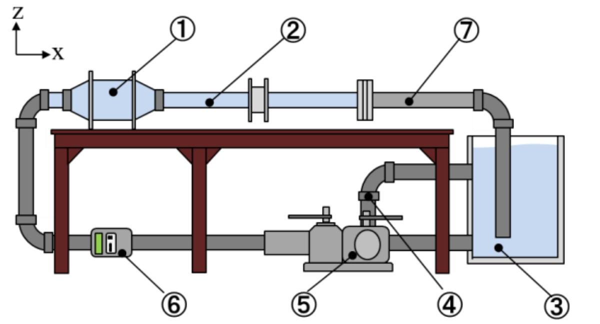


Fig. 3 Conventional planar sensor(left) and developed focusing sensor(right).



1. Straightener	2. Acrylic pipe
3. Reserve tank	4. Bypath
5. Water pump	6. Electromagnetic flowmeter
7. Test section	

Fig.4 Experimental apparatus of the pipe flow rate measurement.

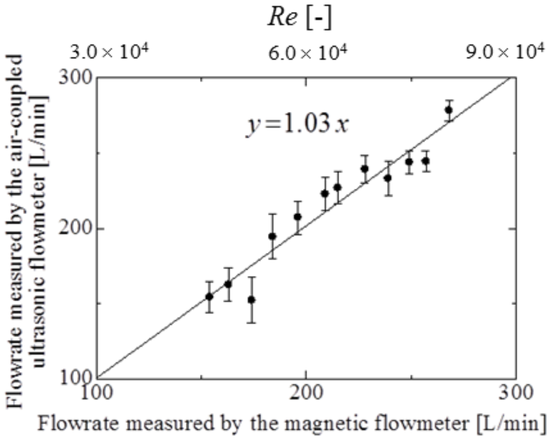


Fig. 5 The result of flow rate measurements.

flowmeter, a test section, and an air coupled ultrasonic flowmeter. Working fluid is tap water, which is stored in a reserve tank and pump to the straightener through the electromagnetic flowmeter. It flows through the test section and, goes back to the reserve tank. The test section is composed of an aluminum pipe. The outer diameter of the aluminum pipe is 60 mm, and the internal diameter is 56 mm. The air-coupled ultrasonic flowmeter is set up at 2500 mm from the outlet of the straightener. The incident angle of air-coupled ultrasonic transducers (Japan Probe, Focusing 0.4K20 × 20N40R) is 2 degree and the distance between the surface of the transducer and the surface of the aluminum pipe is 10 mm. The center frequency of the ultrasonic transducers is 360 kHz, and the transducers have 20 × 20 mm vibration surfaces. The air-couple ultrasonic flowmeter system consists of a Pulser/Receiver (Japan Probe, JPR-10CN), an 8-bit Digitizer (National Instruments, PXI-5114), a PXI-Express Chassis (National Instruments, PXIe-1062Q) that contains a personal computer, an Ext-Amplifier and developed air-coupled ultrasonic sensors. The Ext- amplifier is external electrical amplifier and band-pass filter, to reduce the effect of power-supply noise by pulser-receiver. The electromagnetic flowmeter is set up at the inlet of the straightener

3.2 Result and discussion

The measured average flow rates by the air-coupled ultrasonic flowmeter compared with that by the electromagnetic flowmeter are shown in Fig. 5. The vertical axis means the flow rates measured by the air-coupled ultrasonic flowmeter, and the horizontal axis means the flow rates measured by the electromagnetic flowmeter. The measurement by the air-coupled ultrasonic flowmeter is repeated 200 times. The plots in Fig. 5 show the average of measured flowrates. Error bar shows the standard deviations of measured flow rates. The solid line is drawn by the least-squares method, and the zero point is fixed because of the measurement principle. The slope of the line is 1.03 and the fitting value of R^2 is 0.959. It shows linearity and the capability to measure the flowrate by the focusing sensor. Standard deviations are larger on the lower flowrate, it is caused by the signal processing, and there is limitation of phase resolution due to the sampling speed of the digitizer. Thus, focusing sensor is effective to increase the SNR of receiving signals.

4 MEASUREMENT LINE OF FOCUSING SENSOR BY NUMERICAL SIMULATION

Focusing sensor emits wedge shape beam, and the measurement line is uncertain for the air-coupled UVP development. Verification of the measurement line is required. Therefore, the numerical simulation is performed, employing ComWAVE (CTC) that is based on the voxel finite element method (FEM) and enables to simulate complex models. The model of the air-coupled ultrasonic flowmeter is shown in Fig. 6. There are five materials, material 2 has same speed of sound as aluminum pipe whose outer diameter is 60 mm and inner diameter is 56mm. The material 1 which is contained inside of the material 2 means the water. And material 3 means the air. From the transmitting sensor (material 5), and the model of focusing sensors is the 80 mm diameter cylindrical, 3 mm thickness, and the width is 10 mm. Ultrasound transmits and propagates in the models, and it is received at the receiving sensor (material 4). The distance between the pipe and the sensors is 10 mm. The transmitting signal is 400 kHz, which is the same frequency with the experiment. The boundary condition in the upside,

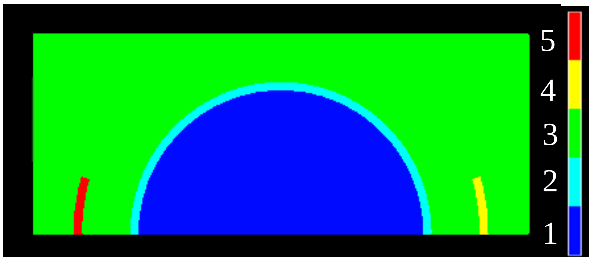
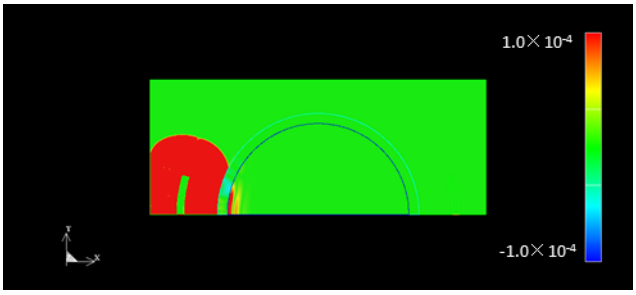
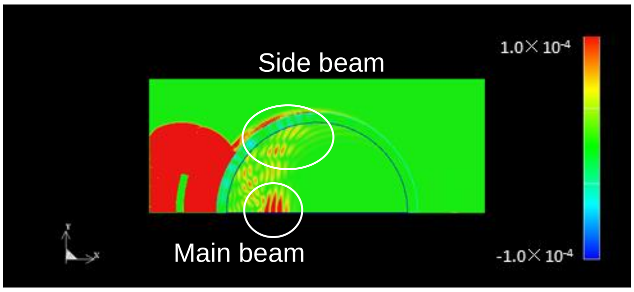


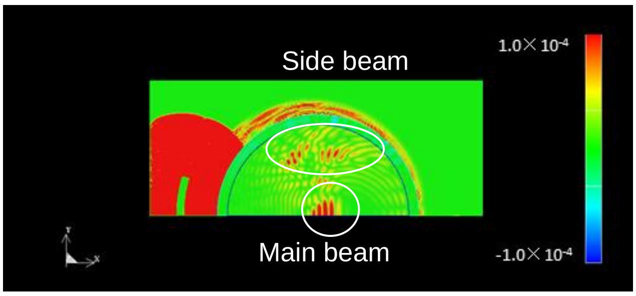
Fig. 6 Models for numerical simulation of the air-coupled ultrasonic flowmeter.



(a) Focusing sensors (35 μs)



(b) Focusing sensors (45 μs)



(c) Focusing sensors (55 μs)

Fig. 7 Results of numerical simulations of ultrasonic propagations in the pipe, contours of the displacement (red: the longitudinal wave, blue: the traverse wave).

right side and left side is absorbing conditions for 400 kHz waves. In order to reduce the number of elements, the model applied symmetry boundary conditions.

The results are shown in Fig. 7. The contour shows displacements of cells and red color shows the component of longitudinal waves, blue shows the component of traverse waves, and green shows zero displacement. In the result, transmitted ultrasound propagates in the air and enters the pipe, and not all of ultrasound propagates as longitudinal waves in the pipe. At the boundary of pipe, the longitudinal wave is converted to the traverse wave, and ultrasound is spread in the pipe in Fig. 7 (b). Therefore, the ultrasonic is focused with an expanse in the center of the pipe, and there is almost same width of the main beam propagates in the center of pipe in Fig. 7 (b) and (c). Therefore, the measurement line is straight from sensor to the sensor by the focusing sensor. However, side beam also occurs along the pipe, and this is one of the incidents to decrease SNR of received signals.

5 CONCLUSION

The focusing ultrasonic sensors are applied to the air-coupled ultrasonic flowmeter to increase SNR of detected signal. For the demonstration of the developed focusing sensor, the aluminum pipe flowrate is measured by the focusing ultrasonic flowmeter and electromagnetic flowmeter. And the result of the measurement is evaluated, and it has linearity to the measurements of the electromagnetic flowmeter. Thus, it shows the air-coupled ultrasound has the capability for TOF flowmeter application, and the focusing sensor is effective to improve the SNR of the received signal in the pipe flow measurement. On the other hand, focusing sensor emits the wedge shape ultrasonic beam, and the measurement line is uncertain for the air-coupled UVP system development. By numerical simulation, the measurement line is almost straight from sensor to sensor. However, focusing sensor causes side beam, which is one of the noises.

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