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A study on ultrasonic liquid flow measurement using non-invasive single-sided array transducer

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1. Introduction

In industrial and medical fields, the ultrasound flow meter has been widely used to measure mass or volumetric flow rate of a liquid or a gas[1)]. The main advantages of the ultrasound flowmeter are high sensitivity, non-invasiveness (e.g., clamp-on and air-coupled methods) and quick respond to the flow change[2)]. The transit-time method is based on the differential transit time of ultrasonic waves between downstream and upstream to determine the liquid flow velocity[3)]. Generally, transit-time flowmeter requires a pair of transducers to transmit and receive ultrasound waves in the downstream and upstream flows[4)]. Designing and installing the transducer pairs are critical factors to decide the accuracy of the ultrasonic flowmeters.

In this study, our goal is to develop methods for estimating the flow measurement using non-invasive single-sided ultrasound array transducer in the case of low liquid flow rate (0 - 50 l/min).

2. Materials and Methods

Experimental setup for the liquid flow measurement through a pipe is shown as in **Fig.1**. The water (2 L reservoir) was circulated by a pump (maximum capacity: 50 liter/min) through the carbon-steel pipe, where the outer diameter, the inner diameter, and the wall of thickness of the pipe were 34 mm, 27.6 mm and 3.2 mm, respectively. The liquid flow rate was controlled by the pump. A mechanical flow meter (i.e., paddle wheel flowmeter) was set up to monitor the reference flow rate. Ultrasound imaging system (Vantage 32LE™, Verasonics, Inc.) with linear array transducer (ATL L7-4) was utilized to acquire the two-dimensional radio frequency (RF) data. The system had 64-transmit and 32-receive channels with sampling frequency at 40 MHz, and was running a transducer with 128 elements and the center frequency at 5 MHz.

Instead of using separate pairs of transducers for upstream and downstream, a single-side array transducer was utilized to alternatively transmit and receive the ultrasonic waves. The upstream and downstream ultrasound beams were transmitted by using 31 elements of the transducer. Then, all 128 elements were utilized to receive the reflected signals from the pipe. Ultrasound beam shapes were controlled by the imaging system. The transmit beam profiles are as shown in **Fig. 2**. The incident angle of the ultrasound path was 20º. The received signals were collected and transferred to the host computer.

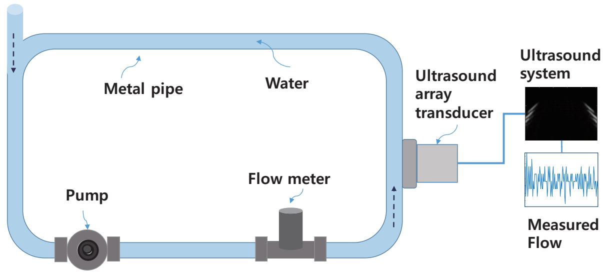

Fig. 1 Experimental setup for liquid flow in the pipe and the flow measurement using ultrasound array transducer.

Fig. 2 Transmit beam profiles for (a) upstream and (b) downstream

The flow velocity affected the ultrasound propagating in the liquid. Therefore, transit-time method was applied to measure the velocity of the fluid. The flow velocity was calculated based on the difference of time-of-flight (TOF) between upstream and downstream. The TOF of upstream t_{up} and the TOF of downstream t_{down} are described as

$$t_{up} = \frac{L}{c - V\sin(\theta)} \quad (1)$$

$$t_{down} = \frac{L}{c + V\sin(\theta)} \quad (2)$$

where L is the ultrasonic path length through the fluid, c is the speed of sound in the fluid, V is average flow velocity and θ is the angle of propagating ultrasonic wave. As the velocity of the liquid flow is much smaller than the speed of sound in general, the equation of flow velocity was derived as

$$V = \frac{c^2(t_{up} - t_{down})}{2L\sin\theta} \quad (3)$$

For the subsample time difference estimation, cross-correlation algorithm with Hilbert zero-crossing method[5)] were applied. The 1st and 2nd reflections in

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the received RF images were utilized for the delay estimation.

3. Result and Discussion

Fig. 3 shows the received RF images using the ultrasound system with array transducer from upstream and downstream in the pipe. The received image shows the 1st reflection returned from the inner surface of the pipe, and the 2nd and 3rd reflections occurred due to the Lamb waves propagated through the pipe wall then reflected from the outer surface of the pipe.

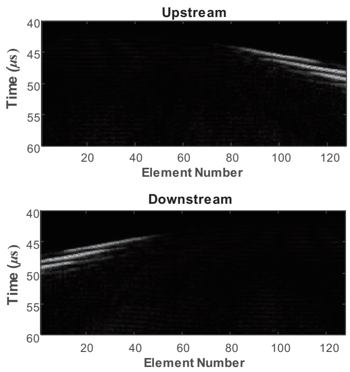

Fig. 3 Received RF images using ultrasound array transducer from upstream and downstream transmits and receives.

Fig. 4 shows the RF signals received from upstream and downstream during no flow (Fig. 4(a)) and flow rate at 36.0 l/min (Fig. 4(b)) in the pipe. When the flow rate was 0 l/min, the RF signals from upstream and downstream matched well. When the liquid was flowing in the pipe, the difference of TOF between upstream and downstream could be clearly seen as shown in **Fig 4(b)**. The time difference was used to measure the flow by Eq. (3).

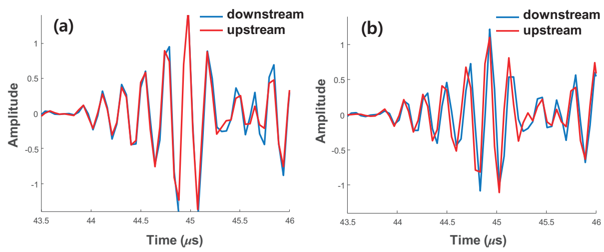

Fig. 4 Received RF signals (a) at no flow, and (b) when liquid is flowing.

Fig.5 shows the liquid flow rates estimated using the 1st (Fig.5 (a)) and 2nd reflections (Fig.5 (b)) received from the array transducer. For the 1st reflection case, the standard deviations of the estimated flow rates #1 and #2 were 0.33 and 1.56, respectively. For the 2nd reflection case, 0.30 and 0.69 were the standard deviations of the estimated flow rates at flow rates # 1 and #2, respectively. It was observed that the estimated flow rate was more stable for the 2nd reflection case. For both of 1st and 2nd reflections, the estimated flow rates fluctuated more when the flow rate was increased. It was expected due to the limited volume of the liquid circulating in the pipe, which will be improved in the future work. Using the linear array transducer with controllable beam shapes and directions, the transmit beams can be adaptively modified for different pipe specifications. Moreover, multiple paths from the Lamb waves can be utilized as the receive signals are acquired from multiple elements simultaneously.

This study demonstrates that non-invasive single-sided array transducer can be utilized to improve the accuracy of the liquid flow rate estimation.

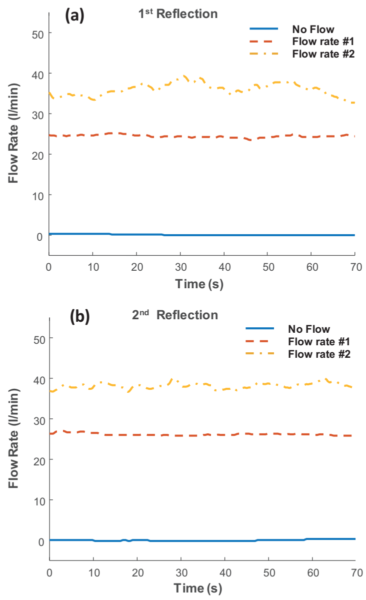

Fig.5 Estimated liquid flow rates using (a) 1st reflections, and (b) 2nd reflections received using array transducer.

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