DETECTION AND MONITORING THE MULTI-PHASE FLOW USING ULTRASONIC WAVE VELOCITY TOMOGRAPHY

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Abstract : This paper presents an application of ultrasonic tomography for detecting the multiphase flow through reconstruction of the cross sectional image of flow. The image is based on the distribution of ultrasonic wave velocity in the flowing medium and reconstructed from measuring the propagation time of ultrasonic wave on the transducers placed around the pipe. We measure the propagation time of ultrasonic wave traveled crossing the pipe from a transmitter to a receiver and we calculate the average velocity as the projection data for the reconstruction process. By using the filtered backprojection algorithm, the image of multiphase flow can be reconstructed.

To validate the proposed method, we performed a computer simulation. We considered that the simulated flow regimes are the combination of water, oil and gas. The flow regimes are simulated in the mathematical model of ultrasonic wave velocity distribution inside the pipe. The simulation results showed that the images produced by the proposed method agree qualitatively with the simulated flow regimes.

Keywords : Ultrasonic tomography, multiphase flow, reconstruction algorithm

1. INTRODUCTION

Nowadays, an instrument, which can be used, for detecting simultaneously the liquid and gas flow rate or condition in a liquid – gas mixture, is a necessary. The information about the flow in a pipeline is important. For example, in the Oil and Gas Industry, such information is useful to determine the process control strategy and to calculate how much the oil and gas have been distributed and sold to the client through the pipeline.

Some research groups now are developing a system that can be utilized to detect accurately the multiphase flow. Some studies are concerned with the development of imaging system for flow measurement. For example, [Isaksen et al, 1993] have developed a system based on capacitance sensor for imaging the multiphase flow.

This paper describes the development of a method for monitoring the multiphase flow using the ultrasonic tomography. Tomography is the cross sectional imaging of an object from projection data collected by illuminating the object from many different directions. The projection data is obtained by measuring at the array of ultrasonic transducers. In this study, the reconstructed image of flow is based on the ultrasonic wave velocity distribution on medium inside the pipe. We used the simulated data for examining the proposed method. The simulated data are obtained by some assumption concerning the pipe size, flowing medium and type of boundary. The measurement data is time of flight ultrasonic pulse and then average velocity of wave through the medium is calculated for the reconstruction process.

2. TOMOGRAPHY METHOD

Consider, $f(x, y)$ represents the characteristic distribution of the object to be studied and each line integral by the (θ, t) parameters. Any straight line in x-y plane can be described as

$$x\cos\theta + y\sin\theta = t \tag{1}$$

The line integral $P_\theta(t)$ is defined as

$$P_\theta(t) = \int_{(\theta,t)line} f(x, y)ds \tag{2}$$

By using a delta function, equation (1) can be rewritten as

$$P_\theta(t) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y)\delta(x\cos\theta + y\sin\theta - t)dxdy \qquad (3)$$

The function $P_\theta(t)$ is known as the *Radon transform* of the function $f(x, y)$. Combining a set of line integrals forms a projection. The simplest projection is a collection of parallel ray integrals.

To reconstruct f from $P_\theta(t)$, we use an algorithm named the filtered back projection algorithm. This algorithm is based on the Fourier Slice theorem. The Fourier Slice theorem states that the 1-dimensional Fourier transform of a parallel projection of an object $P_\theta(t)$ taken at angle θ gives a slice of the 2-dimensional Fourier transform of object function, subtending an angle θ with the u-axis. Define, $S(\omega,\theta)$ is the Fourier transform of $P_\theta(t)$, then the Fourier slice theorem can be expressed as

$$S(w,q) = F(w,q) = F(w\cos q, w\sin q) \qquad (4)$$

where $F(w,\theta)$ is the 2-dimensional Fourier transform of object on polar coordinate.

To obtain the image of the object $f(x, y)$, we need to backproject into space domain. The backprojection process is described as

$$\hat{f}(x, y) = \int_0^p Q_q(x\cos q + y\sin q)dq \qquad (5)$$

where

$$Q_q(t) = \int_{-\infty}^{\infty} S_q(w)|w|e^{j2pwt}dw \qquad (6)$$

The equation (6) represents the filtering operation, where $|\omega|$ is frequency response of the filter. Thus, the equation (6) is called the filtered projection. The equation (5) describes that every the filtered projection should be back projected. If K is the number of projection, then the equation (5) can be written as

$$\hat{f}(x, y) = \frac{p}{K}\sum_{i=1}^{K} Q_{qi}(x\cos q_i + y\sin q_i) \qquad (7)$$

where, $\hat{f}(x, y)$ is the reconstructed object function

3. ULTRASONIC TOMOGRAPHY

The ultrasonic wave propagates from a transmitting transducer through the object and measured by a set of receiver on the far side of the object. We measured the propagation time of ultrasonic wave from the transmitter to the receiver, and then we calculate the average velocity. **Figure. 1.a** shows an example of the propagation of ultrasonic wave in the pipe containing two fluids. Since the flow rate is very small compared to the velocity of ultrasonic wave, we can install the transducers as shown in **Figure. 1.b.** Although the wave propagates with small divergence and undergoes refraction at the boundary between the flowing medium, the wave received at the transducer R is as if it propagates straight from transducer T to transducer R. The straight line between T and R is defined as the measurement path. Thus, the velocity of ultrasonic wave can be calculated by using the following equations. The equations for the propagation time are
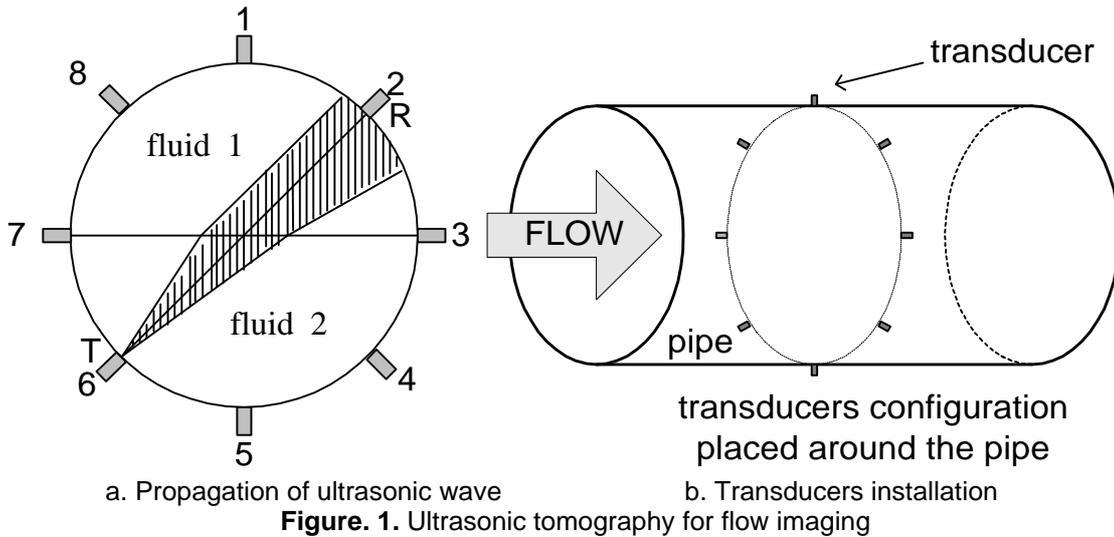
$$T_1 = \frac{X_1}{V_1} \qquad (8)$$

$$T_2 = \frac{X_2}{V_2} \qquad (9)$$

The average velocity is,

$$f = \frac{X_1 + X_2}{T_1 + T_2} \qquad (10)$$

where
    T_1= propagation time through fluid 1
    T_2= propagation time through fluid 2
    X_1= propagation path through fluid 1
    X_2 = propagation path through fluid 2
    V_1= Wave velocity at fluid 1
    V_2= Wave velocity at fluid 2
    f = average velocity

a. Propagation of ultrasonic wave   b. Transducers installation
Figure. 1. Ultrasonic tomography for flow imaging

Consider we use [*n*] transducers. First, we set the transducer no. 1 as a transmitter and transducer no. 2, 3, 4, …*n* as the receivers. Then, we set the transducer no. 2 as the transmitter and transducer no. 3, 4, 5, …, *n*, and 1 as the receivers. This process is repeated until the transducer no. *n* become the transmitter. The data collection process for 8 transducers is shown in **Figure. 2**.

(a)   (b)   (c)
T = Transducer no. 1   T = Transducer no. 2   … …   T = Transducer no. 8
Figure. 2. Data collection technique
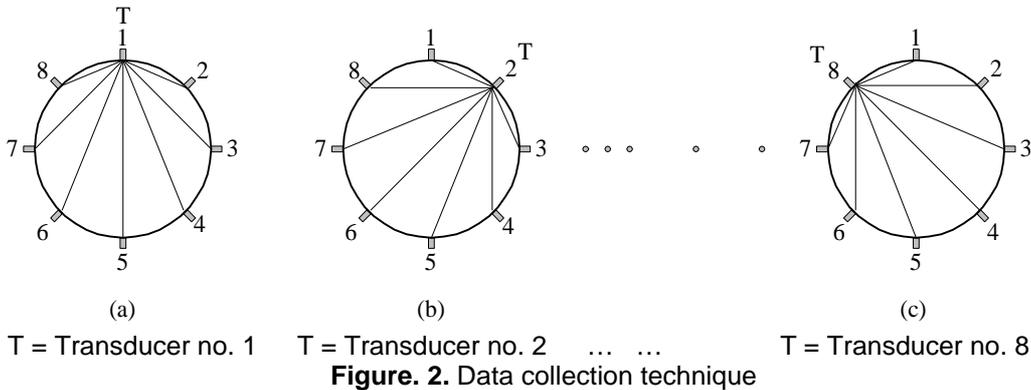
To reconstruct the image of the object based on the wave velocity distribution, we 'measured' the average propagation velocity between two transducers. Since, we use the parallel beam reconstruction algorithm; we re-arrange the path of the propagation in order to obtain the parallel data projection. For example, when we use 8-transducer system, the arrangement of the propagation path is shown in **Figure. 3**.
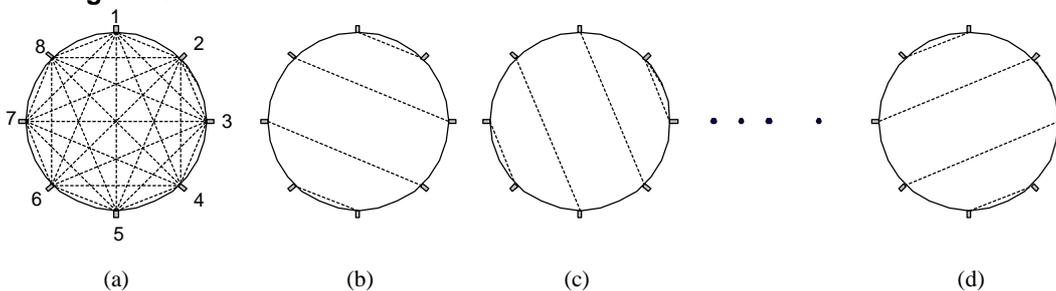
(a)   (b)   (c)   (d)
Figure. 3. Re-arrangement of the measurement path
a.   : The measurement path
b, c, d   : The parallel measurement path

There are only 4 measurement paths in each projection angle, thus we do have only 4 number of data for each projection. In order to obtain the image with good enough resolution, we multiply the number of data by using the spline interpolation method because the number of data obtained from 'the measurement' is very few for the reconstruction process.

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4. SIMULATION

4.1. Flow Modeling

We use 1.0 [m] diameter pipe with a number of transducers installed around the pipe. The transducers are the transceiving transducers, where they can be, as the transmitter or the receiver. The position of these transducers is already shown in **Figure. 2**. In this study, we used 16, 32, and 64 transducers for examining the dependencies of the results on the number of transducers.

We assume that the maximum number of flowing medium is three, and it consists of liquids and gas. The kind of flowing medium and its ultrasonic velocity are shown in **Table 1**.

Table 1. Flowing medium and ultrasonic wave velocity

Medium :	Water	Oil	Gas
Ultrasonic wave velocity [m/second]**:**	1500	1200	340

The models of flow used in this study are depicted in the cross sectional view of the pipe as shown in **Figure. 4**.
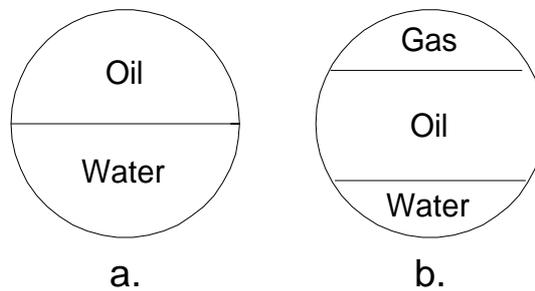

Figure. 4. Simulated flow regimes to be imaged

4.2. Reconstruction Results

In the simulation, two simulated flow regimes were considered as the real object to be identified by the proposed method. We considered a similar situation with the real problem where we placed the transducers around the pipe and installed with the same interval from one to another one. The results are displayed in the normalized gray scale image. **Figure. 5** shows the simulation result for 16-transducer system. **Figure. 6** shows the result for 32-transducer system. **Figure. 7** shows the result for 64-transducer system and **Figure. 8** shows the result for 32-transducer system using interpolation data.
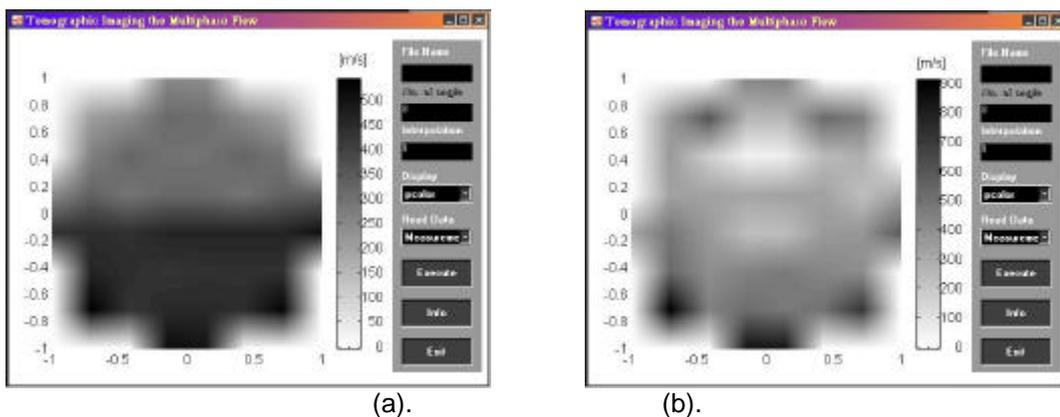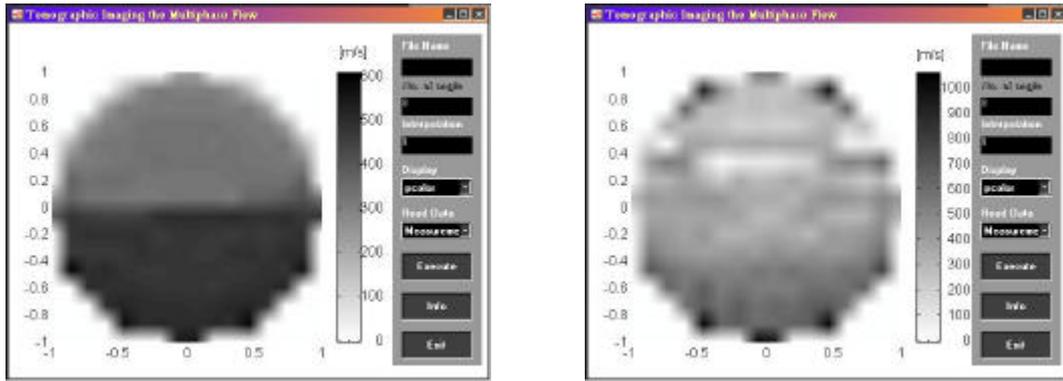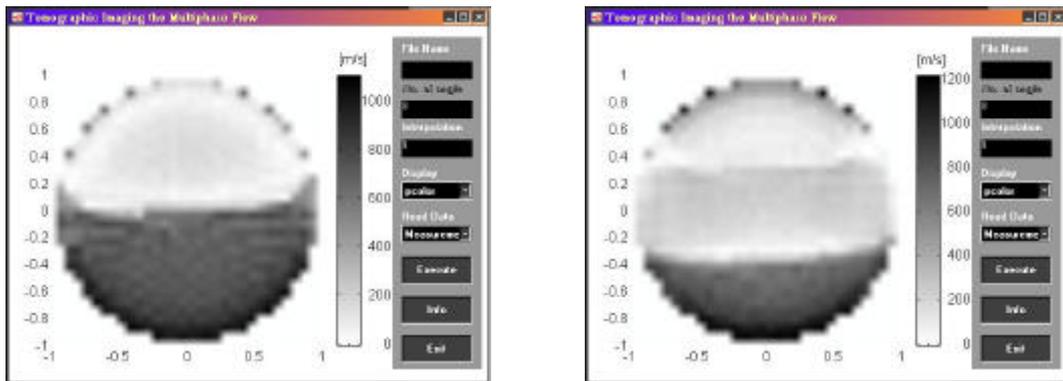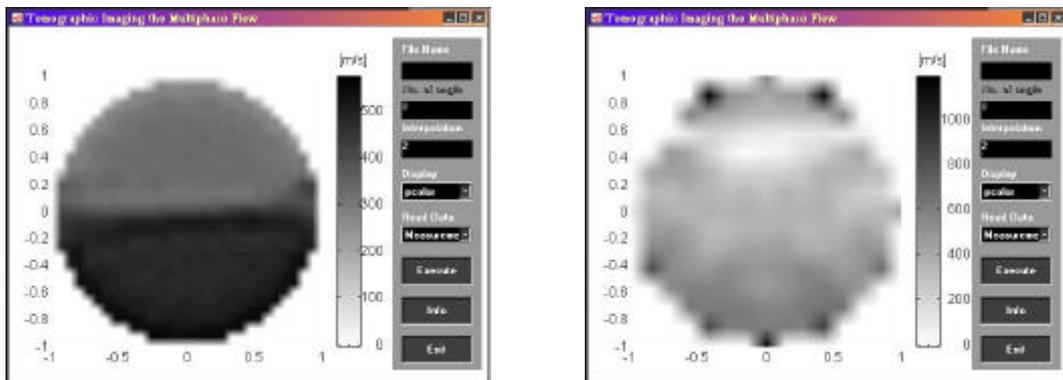

(a). (b).

Figure. 5. Reconstructed results obtained for 16-transducer system

(a).   (b).

Figure. 6. Reconstructed results obtained for 32-transducer system

(a).   (b).

Figure. 7. Reconstructed results obtained for 64-transducer system

(a).   (b).

Figure. 8. Reconstructed results obtained for 32-transducer system with interpolation data

The simulation reveals that it is possible to reconstruct the wave velocity distribution based image of flow process from the 'measurement' of time of flight of ultrasonic wave propagated from transmitter to receiver. The stratified flowing medium of object can clearly be recognized in gray scale image, specifically when the number of transducers used was 64 transducers.

When the number of transducers used were 16 transducers, it can be shown that the image was relatively poor and the object could not, clearly be identified. These reconstructed images have been improved by interpolation of the projection data before the reconstruction process was performed, then the better results have been achieved.

5. CONCLUSIONS

This paper has presented a method for imaging the multiphase flow using the ultrasonic tomography. We employed the filtered back projection algorithm of the straight path tomography for reconstructing the image of flow process from its projection data measured by ultrasonic transducers. We 'measured' the propagation time of ultrasonic wave then the average velocity of the wave was

calculated as the projection data. Before the reconstruction process was performed, we arranged the 'measurement' data in the parallel form, in order to obtain the parallel beam projection data. To obtain more accurate the image when we used limited number of transducers, we have multiplied the number of projection data by using interpolation technique prior to reconstruction process. From the simulation, the clear image was successfully reconstructed, when we used 64 transducers.

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