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**ULTRASONIC FLOW IMAGING SYSTEM:
A FEASIBILITY STUDY**

by

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CONTENTS

ABSTRACT.....	1
1 INTRODUCTION	1
2 ULTRASONIC IMAGING TECHNIQUES	2
2.1 Reflection-Mode Tomography.....	4
2.2 Diffraction Tomography.....	6
3 THE MEASUREMENT SYSTEM.....	7
4 LABORATORY TESTS.....	11
5 CONCLUSIONS	17
ACKNOWLEDGMENTS.....	17
REFERENCES	19

FIGURES

1 B-scan geometries	3
2 Conceptual design of reflection-mode flow imaging system	5
3 Rotating B-scan geometry	5
4 Ultrasonic flow imaging measurement system.....	8
5 Data acquisition time sequence of multichannel imaging system	10
6 Typical laboratory ultrasonic imaging system.....	12
7 Bench-scale two-phase flow loop with square flow channel.....	13
8 Ultrasonic pulses transmitted through the flow channel (A) with and (B) without particles in water.....	14
9 Transmission-mode ultrasonic images constructed from (A) peak amplitude, and (B) time-of-flight.....	15
10 Reflected pulses from the flow channel (A) without, and (B) with particles in water	16
11 Reflection-mode ultrasonic images constructed from (A) peak amplitude and (B) time-of-flight.....	18

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ABSTRACT

This report examines the feasibility and potential problems in developing a real-time ultrasonic flow imaging instrument for on-line monitoring of mixed-phase flows such as coal slurries. State-of-the-art ultrasonic imaging techniques are assessed for this application. Reflection and diffraction tomographies are proposed for further development, including image-reconstruction algorithms and parallel processing systems. A conventional ultrasonic C-scan technique is used to demonstrate the feasibility of imaging the particle motion in a solid/water flow.

1 INTRODUCTION

The complete characterization of a mixed-phase flow such as coal/water slurry requires measurements of flow rate, particle concentration, fluid viscosity, particle-size distribution, and other process parameters such as temperature and pressure. Nonintrusive and on-line instruments are often required for mixed-phase flow monitoring because any flow disturbance may change the flow characteristics. Of all the nonintrusive approaches, ultrasonic methods have been applied most often.¹ In recent years, ultrasonic flowmeters and viscometers have been developed;^{2,3} flowmeters are primarily based on Doppler and cross-correlation methods. Both methods measure the average particle velocity inside the sensing volume defined by the ultrasonic beam width, even though in some cases velocity distribution can be inferred from the Doppler frequency spectrum or from the width of a cross-correlation peak. To date, no on-line flow instrument is available to measure the velocity profiles of a mixed-phase flow. Knowing the velocity profile allows one to

determine the fluid viscosity, which is needed in characterizing a non-Newtonian flow. Attempts were made to obtain mass flow information from ultrasonic flow instruments, but results showed at best a relative measurement.⁴ Particle-size distribution at present cannot be easily resolved by any on-line instrument. Thus, an on-line flow imaging system offers the potential for obtaining complete flow information.

A real-time flow image is always valuable to a process engineer. Optical methods have been applied to many laboratory flow studies,⁵ but such application to flows under harsh environments are very limited. Ultrasonic imaging has been developed to such a high level that many sophisticated imaging systems are commercially available, especially in the fields of medical imaging and nondestructive evaluation. However, applications to flow imaging have only recently been examined.⁶ This report describes a feasibility study of flow imaging by ultrasonic techniques. Preliminary data acquired with a typical laboratory ultrasonic imaging system will be discussed.

2 ULTRASONIC IMAGING TECHNIQUES

Ultrasonic imaging techniques can generally be classified into two types: pulse-echo and transmission imaging methods. Commonly used pulse-echo imaging methods include A-, B-, and C-scans; for practical industrial or medical applications, the B-scan method is used because each scan produces a two-dimensional cross-sectional image. A B-scan image can be obtained by using a linear, sector, arc, or compound-linear scan,⁷ as illustrated in Fig. 1. Scan selection depends on the object's geometry and the extent of penetration depth; the compound-linear scan is generally adopted for its better field of view. The concept of computerized tomography (CT) developed for X-ray imaging has also successfully applied to ultrasonic imaging. Ultrasonic reflection tomography⁸ is an example of CT application to the B-scan method. For a circular aperture, a reflection-mode image is reconstructed from a set of B-scan images acquired from different angular positions of the cross-sectional plane. Reconstruction algorithms have been developed for many practical applications,^{9,10} the

Fig. 1. B-scan geometries

basic concept of the algorithms will be discussed later.

The second ultrasonic imaging method is based on transmission data. Again, the image reconstruction methods depend on the measurement process. When the inhomogeneities are large relative to the ultrasonic wavelength, the wave propagation is characterized by refraction and multipath effects. The conventional X-ray CT method can be applied to this type of near-straight-line transmission approach. On the other hand, when the inhomogeneities become comparable in size to the wavelength, one must consider wave diffraction and scattering from the inhomogeneities. This type of imaging is called diffraction tomography.¹¹

In this feasibility study, both reflection and diffraction tomographies are examined. The evaluation focuses on applications to two-phase flow.

2.1 Reflection-Mode Tomography

Figure 2 shows the main components of a reflection-mode flow imaging system¹². Ultrasonic transducers are mounted on the periphery of a pipe, defining the image plane. The technique of interfacing transducers to a pipe is fundamental to the success or failure of the imaging system. Direct contact or use of acoustic windows (such as the Teflon windows used in the cross-correlation flowmeter¹³) is recommended. The transducers operate in the pulse-echo mode, and B-scans are made from multiple directions. Reflection tomography is more suitable for a two-phase flow in which the particle or bubble size is greater than the ultrasound wavelength. The image-reconstruction algorithm is similar to the conventional X-ray CT approach, which uses the back-projection algorithm. Consider the rotating B-scan geometry shown in Fig. 3, where (x,y) are the coordinates of a cross-sectional plane of the imaged flow medium, and (t,u) are the coordinates defining the propagation direction of the ultrasound.

The B-scan image at a given rotation, θ , can be characterized by

$$b(x,y, \theta) = a(x,y) ** [h_{bt}(x \cos\theta + y \sin\theta) \\ h_{bu}(y \cos\theta - x \sin\theta)] , \quad (1)$$

Fig. 2.
Conceptual design
of reflection-mode
flow imaging
system

Fig. 3.
Rotating B-scan
geometry

where $a(x,y)$ is the object function that represents the cross-sectional distribution of the object parameters in the xy plane, h_{bt} and h_{bu} are the point-spread functions which describe the axial and lateral resolutions, and $**$ represents a two-dimensional convolution. The reconstructed image in (x,y) is given by

$$s(x,y) = \int_0^{2\pi} b(x,y,\theta) d\theta, \quad (2)$$

which is an integrated cross-sectional image projected out from all angles.

2.2 Diffraction Tomography

The same sensing geometry shown in Fig. 2 can be used to obtain a diffraction image of a flow. The array transducers will be pulsed sequentially one at a time and all the transducers will be used to detect the diffracted or scattered signals. The operating frequency will have a wavelength compatible with particle or bubble size; thus, the diffraction effect is important. In principle, diffraction tomography can provide a complete characterization of the flow medium, including particle-size distribution, particle shapes, and particle concentration and velocities. However, such characterization requires a complete description of the scattering phenomena in the mixed-phase flow. To reconstruct an image, one has to solve the inverse scattering problem, which cannot be done at present for a many-particle system. Consider an inhomogeneous scattering object located in the homogeneous region between the transmitting and receiving transducers. The wave equation describing the scattering region is

$$(\nabla^2 + k_0^2) \theta(r) = - F(r)\theta(r). \quad (3)$$

where $\theta(r)$ is the complex amplitude of the ultrasonic field at point r , and k_0 represents the wavenumber of the field in the homogeneous region. $F(r)$ is the object function representing the inhomogeneities. The solution of the wave equation can be represented by

$$\theta(r) = \theta_i(r) + \theta_s(r), \quad (4)$$

where θ_i is the incident field and θ_s is the scattering field, which is given by

$$\theta_s(r) = \iint F(r_0)\theta(r_0)g(r|r_0) dr_0, \quad (5)$$

where g is the Green's function associated with the imaging system. In general, it is impossible to obtain an exact explicit relationship between θ_s and F . Only approximate solutions can be obtained, which assume that the object is weakly inhomogeneous. The commonly used approximation is the first-order Rytov scheme, which, however, is very noise-sensitive in actual computational implementation. In general, a more detailed flow image can be generated with the diffraction tomography method than with the reflection tomography approach, although the latter may be mathematically simpler.

3 THE MEASUREMENT SYSTEM

Although theory is far from providing an exact image interpretation, measurement techniques have been developed and widely applied to medical imaging and nondestructive evaluation. Ultrasonic images can be constructed from peak amplitudes, time-of-flight, or attenuation measurements. Figure 4 shows a proposed imaging system and the suggested major components that can be easily acquired. A pulser that can generate pulses of narrow width ($<1 \mu s$) and a high peak voltage ($>200 V$) is used to excite the transducers. The pulser is connected to the transducers through a multiplexer that functions as a switching system programmed to activate one transmitter for a short time and then provide ample time for received signals to pass through. The multiplexer must also be fast enough to fit in the real-time data acquisition window and provide isolation between the high-voltage pulser and the signal lines. Multiplexing speed depends on the arrangement of the data acquisition

Fig. 4. Ultrasonic flow imaging measurement system

system, that is, the time required for analog/digital (A/D) conversion and signal averaging. Because of a large set of data being processed, parallel processing techniques is there recommended.

Consider a flow channel 5 cm in diameter with a sound speed of 0.15 cm/ μ s; further assume that a total of 10 transducers of 1 MHz each are in the sensor array and that each transducer is 1.27 cm in diameter. The time span in which reflected and scattered signals will reach the receivers is 10 μ s to 35 μ s if the pulse width is 2 μ s. For real-time imaging, separate A/D conversion electronics are required. Hence, the minimum acquisition time is about 40 μ s, or 0.4 ms with 10 averagings of the signals. Production of an image requires 10 sets of data viewed from different angles; therefore, the total time needed to generate an image will be about 4 ms. The proposed data-acquisition time sequence is shown in Fig. 5. The imaging processing computer and software must be capable of downloading about 20 kBytes of data from 10 A/D systems in 1 ms if 2 kBytes of data are collected from each receiver during one scan. The overall scan time of 4 ms is short enough to capture flow transients inside the sensing volume, provided that the flow velocity is less than 3 m/s (which is within the flow-rate range of a typical coal-slurry flow). Based on this analysis, the required instrumentation for the flow imaging is readily available in state-of-the-art equipment.

Both lateral and axial resolution must be considered. In general, lateral resolution can be estimated from the Rayleigh criterion, which is given by

$$R_1 = 1.22 \lambda F/D, \quad (6)$$

where F is the focal length, D is the diameter of the aperture, and λ is the wavelength. For an 0.5-in. transducer of 0.6-in. focal length and 1 MHz in center frequency, the estimated lateral resolution is 22 μ m. In the actual transmission mode of operation, the resolution will be even lower i.e., about 25% smaller than 22 μ m. Axial resolution is unaffected by the focusing effect, but is determined principally by transducer bandwidth.

Fig. 5. Data-acquisition time sequence of multichannel imaging system

The longer the bandwidth, the shorter the acoustic pulse that can be generated and received and the finer the definition along the axis of propagation. A 2.25-MHz transducer with 70% bandwidth, for example, will produce axial resolution of about 20 μm . Therefore, the ultrasonic flow imaging system should be able to resolve particle sizes greater than 20 μm .

4 LABORATORY TESTS

To demonstrate the concept of ultrasonic flow imaging, we conducted laboratory tests with a conventional ultrasonic C-scan technique. Figure 6 shows a typical laboratory setup for C-scan imaging. The transducer assembly can be a single transducer arrangement for the pulse-echo mode of operation or a dual-transducer setup for the transmission mode. A square flow channel of 0.64 cm in depth, shown in Fig. 7, was constructed of Plexiglass and connected to a water reservoir through a laboratory tubing pump. Polystyrene spherical beads were circulated in the flow channel, and both reflection and transmission C-scan images were obtained. In the transmission mode, the transmitted signal is attenuated if particles are present in the beam path; Fig. 8 shows two transmitted pulses whose amplitude difference is due to the presence of particles. Note that there is a slight phase change ($\approx 4 \mu\text{s}$) between the two; this might be directly related to particle size. This observation indicates that diffraction tomography can provide a measure of particle size. Images can be constructed from the amplitude changes and the time-of-flight variations. Figure 9 shows these images scanned with stationary particles suspended in water. Individual particles are not resolved, but a group of particles is identifiable in each image. To resolve individual particles, one must rely on the tomography technique with a reconstruction algorithm based on scattering patterns.

The reflection mode of operation measures backscattering signals from the particles. Reflected signal amplitudes are relatively small, particularly in comparison to the wall reflections of the flow channel. Figure 10 shows two pulse trains in which reflections from particles can be detected in the trailing edge of the last pulse. To produce a reflection

Fig. 6. Typical laboratory ultrasonic imaging system

Fig. 7. Bench-scale two-phase flow loop with square flow channel

Fig. 8. Ultrasonic pulses transmitted through flow channel (A) with and (B) without particles in water

Fig. 9. Transmission-mode ultrasonic images constructed from (A) peak amplitude, and (B) time-of-flight

Fig. 10. Reflected pulses from flow channel (A) without, and (B) with particles in water

image, one must position the gate away from the wall reflections. Figure 11 shows the amplitude and time-of-flight images of particle flow.

5 CONCLUSIONS

We have conducted a feasibility study to evaluate ultrasonic imaging techniques for mixed-phase flow imaging applications. The study covers a brief discussion of the theories of imaging reconstruction and some laboratory test results. Two types of ultrasonic imaging techniques, reflection and transmission tomographics, are discussed. The image-reconstruction algorithms for both techniques still depend on some first-order approximations that assume a uniform and homogeneous flow medium. To obtain a more realistic description of a mixed-phase flow, one might have to include higher-order scattering effects in the reconstruction models. These higher-order algorithms will be the subject of future research. Regarding measurement, two major difficulties require development: these are the (1) front-end transducer interfacing arrangement and (2) parallel processing capability. An effective transducer array design will be further investigated. Overall, application of ultrasonic imaging to real-time monitoring of mixed-phase flows is definitely feasible, but more research and development are needed.

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Fig. 11. Reflection-mode ultrasonic images constructed from (A) peak amplitude and (B) time-of-flight

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