An Investigation on Characterizing Two-phase Flow with Broad-Band Ultrasonic Impedance Spectra

XUE Minghua, SU Mingxu, CAI Xiaoshu

University of Shanghai for Science and Technology, 516 Jungong Rd, Shanghai 200093, CHINA

xmh2000@126.com

Abstract. This paper focus on how to extract sufficient impedance information from ultrasonic signals and utilize them effectively in a two-phase characterization method based on broad-band ultrasonic impedance spectra. After an introduction of ultrasonic velocity and attenuation spectra, a classical model and a broad-band ultrasonic signal technique are introduced simultaneously. The relationship between the ultrasonic impedance and spectrum information is investigated both theoretically and experimentally. With an experimental set-up developed in IPTFM, impedance spectra data are measured by reflection using magnitude and the phase spectrum of signals.

1. INTRODUCTION

In recent years, with the dramatic development in particle concerned fields, dense particulate two-phase flow is very common in different industrial areas and production processes. Among particle sizing methods, ultrasonic spectrum analysis, including attenuation and phase velocity spectra, have gained much attention for characterization of concentrated dispersions, due to its penetration capability in highly concentrated media and advantages of fast and non-invasion test, low cost and endurable set-up. With development of physical model and experimental technique, ultrasonic method permits accurate determination of particle size distribution (PSD) and concentration (Su, et al., 2002). The characterization of two-phase flow by ultrasound requires a formal theoretical basis, a reasonable experimental data, a stable and rapid inversion algorithms. The formal theoretical basis relates the properties of the mixture, particularly the dispersed phase particle size distribution, to the complex wavenumber governing propagation. These propagation problems can be identified two approaches: scattering and coupled phase models (Challis, et al., 2005). A significant scattering theoretical model on acoustical wave propagation in particulate mixtures can be traced back to the Epstein and Carhart (Epstein, et al., 1953). Combined with the work of Allegra and Hawlay (Allegra, et al., 1972), the classical ECAH model was established. This model combined viscous and thermal absorption into scattering, a fully thinking about sound propagation and interaction with particles was made. Riebel (Riebel, et al., 1989) focused on the ultrasonic scattering by particles in short wave limit. He has developed a scattering model by analogism with Lambert-Beer model of light extinction. McClements (McClements, et al., 1991) provided in-depth discussions about droplets size measurement theories in emulsions. He contributed an explicit solution of ECAH in long wave limit. Coupled phase models, as a substitute of scattering models for small hard core particles were studied by Harker (Harker, et al., 1988) and Dukhin (Dukhin, et al., 2002). Such work have provided a possibility for ultrasonic method
to be used in characterizations of colloidal suspensions and emulsions with volume fraction 1% to 50%, size range from 10 nanometer to 1 millimeter.

Most papers focus on the ultrasonic attenuation and/or phase velocity spectrum, which means we should obtain the measurements of frequency dependent ultrasonic attenuation coefficient or acoustic velocity in particulate two-phase flow. In this paper, we use another acoustic parameter, acoustic impedance, describing the ultrasonic spectrum information, establishing the relationship with the classical ultrasonic theoretical models, obtaining the experimental data of acoustic impedance spectrum.

2. PRINCIPLES

There are three major steps in the determination of particle size using ultrasonic spectroscopy: (i) measurement of the ultrasonic parameters spectra of the two-phase flow and (ii) interpretation of the resulting spectra using a suitable theory and (iii) a stable and rapid inversion algorithms. To obtain accurate measurements it is necessary to carry out three steps carefully (Su, et al., 2004).

2.1 Ultrasonic spectroscopy methods

Ultrasonic spectroscopy utilizes measurements of the frequency dependence of the ultrasonic velocity and/or attenuation coefficient of colloidal dispersions to obtain information about the concentration and particle size distribution of colloidal particles. The velocity at which an ultrasonic wave propagates through a particulate suspension, and the amount by which it is attenuated, are governed by interactions between the ultrasonic wave and the particles, e.g. transmission, reflection, absorption, and scattering. Ultrasonic spectroscopy has advantages over many existing particle-sizing technologies because it is non-destructive and non-invasive, is capable of rapid measurements and can be used to characterize systems which are concentrated and optically opaque (McClements, et al. 1997).

Characterizing the two-phase flow relies on being able to measure the frequency dependence of the ultrasonic parameters, including velocity, attenuation, and impedance. The ultrasonic velocity is the distance the ultrasonic wave moves through the sample per unit time, whereas the attenuation coefficient is a measure of the decrease in the amplitude of the ultrasonic wave per unit distance travelled. The ultrasonic velocity and attenuation spectra can be determined by the following:

\[ X(\omega) = \exp\left(\frac{-i\omega x}{c(\omega)}\right)\exp\left(-\alpha(\omega)x\right) \]  \hspace{1cm} (1)

Where the \( X(\omega) \) is the response of the time domain original signal by the fast fourier transform (FFT). \( X \) is the position of the ultrasonic wave in the sample at the certain time. The first exponential term represents the phase shift applied to the acoustic signal while propagating distance \( x \) through the sample at the phase velocity \( c(\omega) \). The second term represents the attenuation of the signal travelling over the same distance. The individual velocity and attenuation spectra can be written as following by the real and imaginary part separation of Eq.(1).

\[ c(\omega) = \frac{\omega(x_2 - x_1)}{\theta_2(\omega) - \theta_1(\omega)} \]  \hspace{1cm} (2)

\[ \alpha(\omega) = -\frac{1}{x_2 - x_1} \ln \left| \frac{X(\omega)_2}{X(\omega)_1} \right| \]  \hspace{1cm} (3)

Where the \( \theta \) and symbol \( | | \) mean the phase and magnitude of the \( X(\omega) \). The subscripts 1 and 2 refer to the different positions, respectively.

The acoustic impedance of a material is important because it determines the fraction of the ultrasonic wave that is reflected from its surface. The specific acoustic impedance is defined as the ratio of the
acoustic excess pressure \( (P) \) and the particle velocity \( (U) \). Generally, the impedance is complex and can be divided into the real and imaginary part.

\[
Z = \frac{P}{U} = R_z + i \cdot X_z
\]

(4)

Where \( R_z \) is called the resistive component and \( X_z \) is called the reactive component. Like the ultrasonic velocity and attenuation coefficient, the acoustic impedance is a fundamental physical characteristic. Measurements of acoustic impedance can therefore be used to provide valuable information about the properties of two-phase flow.

2.2 Broad-band ultrasonic spectra
In principle, a spectrum at three frequencies could afford basic data for inversion computation to extract particle size information. But such a spectrum has hardly been used in inverse computations just because it is inadequate to overcome multiple solution problems and random error disturbance in ill condition equations. A broad band spectrum at a series of frequencies, in contrast, shows advantages to ensure stable solutions.

There are at least three techniques to obtain broad band ultrasonic spectrum: transducers array, scanning frequency and the fast fourier transform (FFT). Compared with other two methods, FFT technique has advantages of rapid test and easily handling set-up, which is critical for on-line measurement.

In the FFT method, a signal generator is used which is capable of producing a broad-band electrical pulse which contains a wide range of frequencies. This pulse is applied to the transmitting transducer where it is converted into a broad-band ultrasonic pulse. After the pulse has travelled through the sample it is detected by the receiving transducer. The frequency dependence of magnitude and phase of the pulse are determined using a FFT technique. Generally, the ultrasonic velocity is determined from the phase, the ultrasonic attenuation coefficient is determined from the magnitude, and the ultrasonic impedance is determined from both phase and magnitude.

Fig.1 shows the original signal. Fig.2 and Fig.3 show the magnitude and the phase spectrum using FFT technique.

Fig.1 Original signal  Fig.2 Magnitude spectrum  Fig.3 Phase spectrum

2.3 Ultrasonic parameters spectra from theoretical model
Once the ultrasonic parameters spectra of two-phase flow have been measured, it is necessary to convert them into concentration and particle size distribution using an appropriate theory. Theories are based on a mathematical treatment of the physical processes that occur when an ultrasonic wave propagates through an ensemble of particles suspended in two-phase flow. The comprehensive and classical model is based on single scattering theory: Epstein, Carhart, Allegra and Hawlay (ECAH) model.

\[
\left( \frac{K}{k_c} \right)^2 = 1 + \frac{3\phi}{ik_c^3 R^3} \sum_{n=0}^{n} (2n+1)A_n
\]

(5)

For the monodisperse particle system, the velocity and attenuation spectra can be represented as:
\[ \alpha(\omega) = -\frac{3}{2k^2} \sum_{j=1}^{N} \frac{\phi_j}{R_j^2} \sum_{n=0}^{\infty} (2n+1) \text{Re}(A_n(R_j, \omega)) \]  
\[ C(\omega) = \left( \frac{3}{2\omega k^2} \sum_{j=1}^{N} \frac{\phi_j}{R_j^2} \sum_{n=0}^{\infty} (2n+1) \text{Im}(A_n(R_j, \omega)) + \frac{1}{c_w} \right)^{-1} \]

Where \( K = \omega/c_s + i\alpha_s \) is the complex propagation constant, \( c_s \) is the ultrasonic velocity and \( \alpha_s \) is the attenuation coefficient of the two-phase flow. \( K_c \) is the complex propagation constant of the continuous phase, \( \phi \) is the dispersed phase volume fraction, \( f = 2\pi f \) is the angular frequency, \( f \) is the frequency, \( i = \sqrt{-1} \), and \( R \) is the particle radius. The \( A_n \) terms are the scattering coefficients of the various types of waves scattered from the individual particles. \( \text{Re} \) and \( \text{Im} \) is real part and imaginary part of the complex number.

The ultrasonic impedance of the two-phase flow can be related to its physical and acoustic complex propagation constant by the following expression:

\[ Z = (\omega \rho)/K \]  

Where \( \rho \) is the angular frequency, \( \rho \) is two-phase flow density and \( K \) is the propagation constant. In the model analysis, the mathematical result is usually given by the style of the propagation constant \( K \). Eq.(8) shows the relationship between the ultrasonic impedance and the theoretical model. The numerical calculation of frequency dependence of the ultrasonic impedance can be obtained by the suitable ultrasonic theoretical models.

### 3 EXPERIMENTAL METHODS AND DATA ANALYSIS

An ultrasonic measurement set-up showed in Fig.4 was developed to obtain testing data of frequency dependent ultrasonic attenuation. Ultrasonic waves, generated by broad-band ultrasonic transducer(V317-SU) worked with an ultrasonic pulser/receiver (PR5800, Parametric, Inc), transmit through two-phase flow in a cell, and reflected, in which signals could acquired by high-speed data acquisition card, and recording in a personal computer. The ultrasonic transducer could be designed as a style of probe, being convenient for on-line measurement in particulate two-phase flow.

![Fig.4 Schematic diagram of ultrasonic system](image)

![Fig.5 Schematic diagram of cell](image)

Fig.5 shows the schematic diagram of the measurement cell (McClements, et al., 1991). The transducer generates a pulse of ultrasound which travels along the buffer rod until it reaches the interface where it is partly reflected and partly transmitted. The impedance of a sample is determined by measuring the amplitude of the pulse reflected from the buffer rod/sample interface. The velocity is determined by measuring the time different between the first echo and the second echo, whilst the attenuation coefficient is determined by measuring the amplitude of these two echoes. The magnitude (\( M \)) and phase (\( \theta \)) of the pulse were measured as a function of frequency using Fourier transform analysis. This procedure was carried out for the sample being analyzed, as well as for a calibration material with known acoustic properties, i.e., distilled water (Asylbek, et al., 2000). Fig.6 shows the
measured ultrasonic signal when the buffer rod material is the plexiglass, and Fig.7 shows the measured signal when the buffer rod material is the steel plate. In these experiments sample is the distilled water. The impedance of water is similar to the impedance of plexiglass, so large part of ultrasonic wave can transmit into the sample. On the contrary, the impedance of steel is large compared to the impedance of the plexiglass, so the multiple echoes can be obtained as shown in Fig.7.

The reflectance was then calculated at each frequency using the following formula:

\[ R_s = R \frac{M_i}{M_c} \exp \left( i \left( \theta_i - \theta_c \right) \right) \]  \hspace{1cm} (9)

Where \( R \) is the reflectance, and the subscripts \( S \) and \( C \) refer to the sample and calibration material, respectively. The physical properties of the calibration material (i.e., distilled water) and the buffer rod are known, so the value of \( R_c \) can be easily calculated. From the reflectance \( R \), the acoustic impedance can be represented as the following equation:

\[ Z_s = Z_{BR} \frac{1 - R_s}{1 + R_s} \]  \hspace{1cm} (10)

Where \( Z_{BR} \) is the acoustic impedance of the buffer rod, and the \( Z_s \) is the acoustic impedance of the sample. From Eq.(9), the reflectance \( R_s \) is a complex number, and so the acoustic impedance \( Z_s \) is also complex in Eq.(10). That means it is possible to get the impedance spectra information of two-phase flow by these experimental and computational methods.

For the purpose of obtaining the density and concentration simultaneously, we chose the buffer rod of steel to obtain the impedance spectra. Using this device, the sample density and concentration can be determined by multiple reflections within the steel. More details can be seen the references(Xue, et al., 2008; Margaret, et al, 2002).
concentrations are same (1.5vol%). The experimental data shows it is feasible to obtain the ultrasonic impedance spectra by reflection using magnitude and the phase spectrum of signals.

4 CONCLUSIONS

Three ultrasonic parameters spectra methods have been described which are based on measuring the frequency dependent ultrasonic parameters. Broad-band ultrasonic signal technique is introduced and qualified as magnitude and phase spectrum according the fast fourier transform. The relationship between the ultrasonic impedance and spectrum information is investigated both theoretically and experimentally. For the purpose of characterization of impedance spectra, the special experimental set-up is developed. Our theoretical results and experimental data have showed ultrasonic impedance spectra could provide the new method besides these ultrasonic velocity and attenuation spectra methods.

ACKNOWLEDGEMENTS

The Authors gratefully thank the National High Technology Development 863 Program (2006AA03Z349) and the National Natural Science Foundation of China (No.50706029).

REFERENCES

Su M.X. et al. (2002). "The numerical study of acoustical attenuation and velocity in the suspensions of superfine particles. " ACTC ACUSTICA., 27(3), pp 218-222.

R E Challis. et al. (2005). "Ultrasound technique for characterizing colloidal dispersions." Rep Prog Phys. 68, pp 1541-1637.

Epstein P.S. et al. (1953). "The Absorption of Sound in Suspensions and Emulsions: I. Water Fog in Air. " J. Acoust. Soc. Am. 25, pp 553-565.

Allegra J.R. et al. (1972). "Hawley S.A. Attenuation of Sound in Suspensions and Emulsions: Theory and Experiments." J. Acoust. Soc. Am. 51, pp 1545-1564.

Riebel U. et al. (1989). "Loffler F. The fundamentals of particle size analysis by means of ultrasonic spectrometry." Part.Part.Syst.Charact. 6, pp 135-43.

McClements D J. et al.(1991). "Ultrasonic Characterisation of Emulsions and Suspensions. Advances in Colloid and Interface Science." 37, pp 33-72.

Harker A.H. et al.(1988). "Temple. J.A.G. Velocity and Attenuation of Ultrasound in Suspensions of Particles in Fluids." J.Phys. D: Appl.Phys. 21, pp 1576-1588.

Dukhin A.S. et al.(2002). "Ultrasound for Characterizing Colloids Particle Sizing, Zeta Potential, Rheology." Elsevier, pp 117-135.

Su M.X. et al.(2004). "The measurement of particle size and concentration in suspensions by ultrasonic attenuation." ACTC ACUSTICA.29(5), pp 440-444.

McClements D J. et al.(1997). "Ultrasonic Measurements in Particle Size Analysis. Encyclopedia of Analytical Chemistry." ISBN 0471 976709.

McClements D J. et al.(1991). "Ultrasonic pulse echo reflectometer." Ultrasonic. 29, pp 58-62.

Asylbek K. et al.(2000). "Characterization of aerated foods using ultrasonic reflectance spectroscopy." Journal of Food Engineering, 46, pp 235-241.
Xue M H. et al. (2008). "The experimental study on measurement of density for two phase flow with ultrasonic multiple echo reflection method." Journal of Engineering Thermophysics. 29(8):1343-1346.

Margaret S. et al.(2002). "Ultrasonic Sensor to Measure the Density of a Liquid or Slurry during Pipline Transport." Ultrasonics, 40, pp 413-417.