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Particle characterization in highly concentrated suspensions by ultrasound scattering method

R. Weser[b,1], S. Wöckel[a,*], U. Hempel[a,2], B. Wessely[b,3], J. Auge[c,4]

[a] Institut für Automation und Kommunikation e.V., Werner-Heisenberg-Str. 1, 39106 Magdeburg, Germany
[b] Institut für Verfahrenstechnik und Umwelttechnik, TU Dresden, Dresden, Germany
[c] University of Applied Sciences Magdeburg-Stendal, 39011 Magdeburg, Germany

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ABSTRACT

A method for inline characterization of randomly moving particles in high concentrated suspensions by measuring the back-scattered ultrasonic signals is described. Instead of the single amplitude signal the statistical features of multiple consecutive scattered sound waves are used that represent the scattering amplitude and its decrease over time. Those simple parameters, deduced from the signal, correlate with the particle size and concentration and deliver equivalent information like the attenuation calculated by conventional extinction measurements for particle characterization. For empirical validation of this assumption by two samples, the exponential decrease of the standard deviation was compared with the attenuation measured with a transmission-mode ultrasonic spectrometer. Especially the dependency for high particle concentration is shown. To provide a high spatial resolution and range – in case of media with high attenuation – ultrasonic sensors with a high bandwidth and intensity are used.

1. Introduction

The inline monitoring of suspensions with a high concentration of particles needs the characterization of different parameters like particle size, distribution and concentration which are recommended for quality control in industrial processes. Nowadays there is a large variety of measurement techniques for the determination of particle size and concentration in suspensions and emulsions. Despite this, only few techniques facilitate the characterization of highly concentrated dispersions, e.g. during process monitoring. Especially in case of high particle concentration the applicability of common optical methods is limited to laboratory applications because of the opacity. In contrast, ultrasonic extinction methods are able to overcome this limitation and can provide a benefit concerning inline measurements. Those ultrasonic measurements are capable to deliver additional information on liquid multiphase systems and suspensions, which are not accessible by conventional optical methods for particle characterization. The common particle measurement technique, the ultrasonic attenuation spectroscopy, uses a transmission arrangement for measuring the portion of sound which is extinguished by the suspension. Two acoustic transducers are arranged face to face with a gap between them (Fig. 1a). An equivalent measurement can be performed using a reflector instead of the second transducer. In this case, the transmitted path length is twice the gap width. This gap, which contains the medium to be measured, mostly can be adjusted to ensure a maximum signal-to-noise ratio for the transmission signal. The processing of the ultrasonic transmission and extinction enables the calculation of an attenuation coefficient. The frequency dependent attenuation contains information on particle dimension, distribution and concentration [1].

Due to the increased ultrasonic attenuation, caused by high particulate content, the conventional transmission methods require a small measuring gap, usually in the range of a few millimetres. Those small gaps are vulnerable for blockage by single coarse particle or highly viscous media and do not provide reliability or inline-capability. Alternatively, this article presents a simple method for overcoming this problem by using ultrasonic scattering techniques applying at least one transducer in pulse-echo-(reflection)-mode and analysing the reflected signals that contain the information on the particle system. Taking advantage of this ‘particle-born’ sound signal, it is possible to arrange an ‘open’ measurement setup in reflection mode without any gap (Fig. 1b). Already, there are some applications, which analyse the backscattering signal to calculate the attenuation that is influenced by obstacles and used it for the characterization of biological tissue or

* Corresponding author. Tel.: +49 0391 9901 430; fax: +49 0391 9901 591/590.
E-mail addresses: robert.weser@tu-dresden.de (R. Weser), sebastian.woeckel@ifak.eu (S. Wöckel), ulrike.hempel@ifak.eu (U. Hempel), benno.wessely@tu-dresden.de (B. Wessely), joerg.auge@hs-magdeburg.de (J. Auge).
1 Tel.: +49 0351 46335226; fax: +49 0351 46337058.
2 Tel.: +49 0391 9901427; fax: +49 0391 9901590.
3 Tel.: +49 0351 46336321; fax: +49 0351 46337058.
4 Tel.: +49 0391 8864388; fax: +49 0391 8864126.

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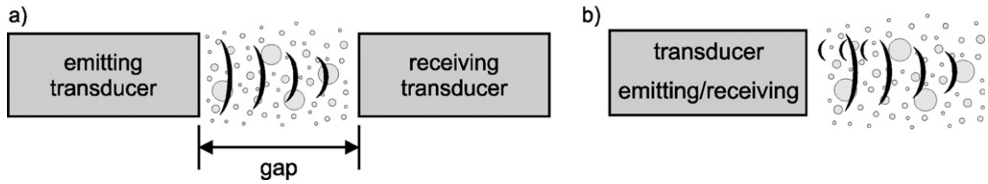

Fig. 1. Common setups for ultrasound measurements: (a) transmission (extinction) setup with at least two transducers, including the medium within a measuring gap; (b) reflection or (back-) scattering setup with at least one transducer.

solid materials [2,3]. Here the calculation of the attenuation needs sophisticated information on the transducers spatial transmit and receive function as well as the ultrasonic field within the media [4]. Usually, such informations are not accessible under industrial process conditions.

The current approach bases on the scattering on randomly moving particles and uses the standard deviation of the measured time-domain (reflection) signal to characterize particles within a fluid system. Here the standard deviation is considered as a level for the back-scattering amplitude. Since no attenuation is derived, in first step, the method does not need any further information on the media or the ultrasonic system. Rather, the decrease of the signals standard deviation – as a simple parameter – is calculated. This parameter does not equal the attenuation but it delivers an equivalent information on the (sound degrading) influence of particles.

The novelty of the presented approach is mainly the statistical evaluation of the gathered reflection signals as well as its applicability for suspensions with a high particle concentration and the non-intrusive probe design related to industrial applications. Prospective industrial applications for such a system are the process monitoring of opaque systems like paints, conditioning of mineral or clearing sludge and saw suspension for semiconductor production.

2. Propagation of ultrasound waves in dispersions

Unlike the propagation of sound in continuous media, sound propagation in suspensions coincides with sound scattering due to the presence of particles. In general, scattering describes a redirection of the sound wave incident on an obstacle (e.g. particle). The scattering behaviour is essentially determined by the size-to-wavelength ratio (between particle size x and sound wavelength λ, respectively sound frequency f), expressed in the form of the dimensionless wave number

$$ka = \frac{2\pi}{\lambda} \cdot \frac{x}{2} = \frac{\pi \cdot f \cdot x}{c}, \qquad (1)$$

where c denotes the sound velocity in the continuous phase. Additionally, it is affected by the acoustic contrast between particle and surrounding medium (i.e. the difference with regard to acoustic impedance) [5]. For small values of ka ($ka < 0.1$), the propagation of sound waves in dispersions furthermore is affected by visco-inertial and thermal effects (ECAH and coupled phase theories) [6–8,1]. Moreover, with further decreasing values of ka, scattering itself becomes rather weak. In backscattering mode, the redirection of the sound waves impinging on the particles of the dispersion causes the detectable reflection signal. Hence, for dispersions containing very small particles ($ka \ll 0.1$) the acquisition of backscattering signals is quite challenging and limited by the signal-to-noise ratio of the measurement system. Against this background, the authors prefer a single scattering model that was developed by Faran [9].

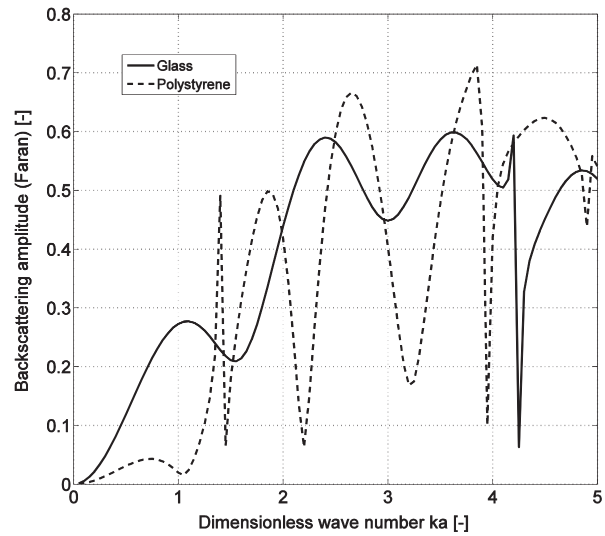

Fig. 2. Backscattering amplitude (relative to the amplitude of the incident wave) versus dimensionless wave number ka for a single glass/polystyrene sphere surrounded by water (calculated using Faran's model and material parameters from Table 1).

In contrast to the ECAH or coupled phase theories,[5] Faran's model does not have any restrictions regarding particle size and can be applied to solid and fluid particles because longitudinal as well as transverse waves inside the particle are taken into account. Because it does not take into account visco-inertial or thermal effects, it is only capable to predict effects of (elastic) scattering.

Fig. 2 shows the backscattering amplitude (relative to the amplitude of the incident wave) for two different particle media. One can see a non-monotone curve shape of backscattering amplitude versus ka, oscillating for $ka > 1$. For $ka < 1$ the backscattering amplitude for polystyrene is quite smaller than for glass due to the difference in acoustic impedance. In general, the lower the acoustic contrast between dispersive and continuous phase, the lower is the backscattering amplitude. Exemplary assuming a frequency of 10 MHz for the incident wave, the backscattering amplitude for a 10 μm ($ka = 0.21$) glass particle surrounded by water is approximately 100 times higher than for a 1 μm ($ka = 0.02$) particle but at once 40 times less than the amplitude of the incident wave. This example clearly shows the advantage of using ultrasonic backscattering for particle sizing as well as the challenge of capturing ultrasonic signals with amplitudes far below the emission level.

Besides the scattering of sound (in the sense of a redirection of the incident wave), which can be considered to be the source of backscattering signal, both the emitted as well as the scattered waves are attenuated while travelling through the suspension.

[5] Explicit formulations for the ECAH theory only can be stated for the long wavelength or small particle size limit ($ka < 0.1$). Coupled phase models, for principal reasons, are not capable to account for scattering effects and therefore are also limited to $ka < 0.1$.

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