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Monitoring local solids fraction variations in multiphase flow using pulse-echo ultrasound

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Abstract

This paper presents an ultrasonic pulse-echo technique for on-line monitoring of variations in solids concentrations in particle suspensions. The method is based on time-frequency analysis of the backscatter signals, exploring variations in spectral content of the backscatter as function of depth in the suspension. Experiments on a settling of magnetite particles in water, at varying solids concentrations, show that the settling process can be followed by studying the energy of backscattered ultrasound.

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Keywords: Flow measurement; Multiphase flow; pulse-echo ultrasound; mass fraction measurement

1. Introduction

In the mining industry, magnetite particles are transported in suspensions with water through different stages of the process. In some of these stages, it is of interest to monitor both the concentration and particle velocity over a cross-section of the flow, e.g. to develop models for efficient control of the unit processes.

Previous work by Stener et al. (2013) and Stener (2013) focused on using pulse-echo ultrasound for flow velocity profile measurements. When used for velocity measurements the pulse echo ultrasound method provided non-intrusive measurements, operation by a single transducer element, relatively good spatial resolution, operation in opaque suspensions, and a fast sampling rate.

Hunter et al. (2012b) studied settling and movement of the settling interface (see Fig. 1). Studying homogeneous suspensions, they also found a linear decay on a dB scale of backscatter strength with suspension depth was found (40-160 mm from the transducer). Hunter et al. (2012a) compared experimental data to backscatter theory, this suggested that the single scattering theory is invalid for systems with particle concentrations greater than 0.1 vol%.

Wöckel et al. (2012) used a narrow measurement cell, resembling what can be found e.g. in analytical instruments. Linear correlation was found between suspension solids concentration and the signal amplitude standard deviation. The measurement depth was e.g: 16 mm in a suspension of 4.5 vol% solids and 5 mm in a suspension of 30 vol% solids. Weser et al. (2013a,b) used the same setup as Wöckel et al. (2012), and studied how peak backscatter amplitude

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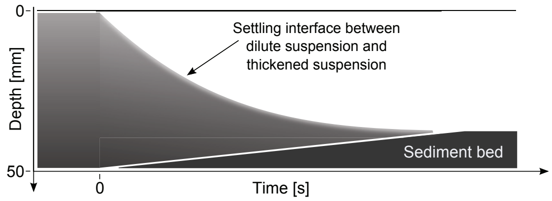

Fig. 1. Sketch of suspension settling, dark color indicates high particle concentration. Before time 0 a turbulent flow of suspension goes through the flow cell. As the pump is decelerated to a stop the suspension starts to settle, and a sediment bed begins to form on the bottom of the cell.

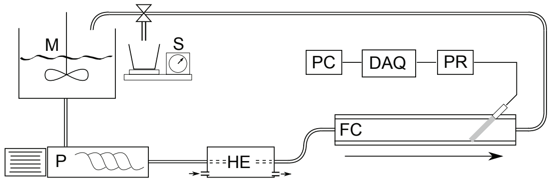

Fig. 2. Experimental setup consisting of mixer (M), pump (P), heat exchanger (HE), flow cell (FC). Also sampling position (S) and data acquisition equipment; pulser-receiver (PR), digitizer (DAQ) and computer (PC), is shown.

increases with mean particle size. Using a 6 MHz transducer good correlation was found for mean particle sizes between 10-54 μm, and using 10 and 14 MHz transducers good correlation was found for particle sizes of 7-23 μm.

In the current work, the aim is to analyze the Power Spectral Density (PSD) of the backscattered signal to extract information about variations of local solids concentration. This paper is a continuation of the work presented by Stener et al. (2014).

2. Experimental setup

Magnetite suspensions with controlled solids concentrations are pumped through a closed rectangular channel. When the pump is stopped, pulse-echo ultrasound is used to monitor the settling process. Ultrasound pulses are transmitted into the suspension and the resulting backscatter is treated as random signals carrying information about the suspension. The signal statistics vary with solids concentration, particle size distribution, particle density, etc.

The experimental setup (Fig. 2) consists of a flow cell (50x75 mm) connected to the support equipment in closed loop described in detail in Stener (2013). The measurements are made using a 2.25 MHz immersion transducer, Olympus V306 (www.olympus-ims.com). The transducer is mounted at a 45° inclination at the end of the channel. The transducer is connected to a pulser-receiver (Panametrics 5800PR, www.olympus-ims.com), which was triggered by an Arduino Duemilanove running custom software. The received backscatter signal is sampled at 100 MS/s an ADQ214 digitizer (www.spdevices.com). The material used is a finely ground magnetite powder (d_{50} = 34 μm, density 5.0 kg/dm^3). The dry powder is mixed with water to reach desired concentrations. The stated concentrations are measured by sampling the stream, at (S) in Fig. 2.

An experiment is conducted as follows: The flow speed is kept at 1 m/s for at least 60 s, to ensure sufficient mixing of the suspension. The pump is then stopped and data acquisition is initiated. During 10 s, pulses are transmitted at a PRF of 200 Hz and their echoes are sampled. When the pump is stopped the suspension begins to settle, see Fig. 1, creating a region with a strong concentration gradient; a settling interface. If the particle concentration is low enough the settling proceeds at a constant velocity. However, when solids concentration below the settling interface becomes high enough the style of settling changes from free to hindered settling, reducing the settling velocity.

3. Theory

In each measurement, the ultrasound transducer transmits a short pulse into the flow. The backscattered sound from the particles in the flow is then sampled using the digitizer and stored as the signal $p[n]$, $n = 0, 1, \ldots N-1$. This signal, $p[n]$, is random by nature, and due to attenuation and multiple scattering (in high concentration suspensions), the underlying random process can not be assumed to be stationary. This means that the signal characteristics will vary as a function of depth, local mass fractions, etc. For a short segment of $p[n]$, however, we may assume stationarity, at least in a wide sense. So, let

$$x_k[m] = p[k+m], \tag{1}$$

where k is the position of the window, $m = 0, 1, \ldots M-1$, and the window length $M \ll N$. In other words, $x_k[m]$ is an M samples long segment of $p[n]$, starting at sample k. The autocorrelation sequence of $x_k[m]$ is defined as $r_{x_k}[l] = E\left\{x_k[m+l]\, x_k^*[m]\right\}$, where $(\cdot)^*$ denotes complex conjugate and l is the lag. Assuming $x_k[m]$ is real-valued and stationary, this can be estimated from the measurements as

$$\widehat{r}_{x_k}[l] = \frac{1}{M}\sum_{m=0}^{M-1} x_k[m+l]\, x_k[m]. \tag{2}$$

Thus, the autocorrelation sequence is a measure of how similar the signal is to a delayed version of itself, with the delay l (see e.g. Hayes (1994)).

The spectral contents, i.e. the PSD, of $x_k[m]$ can be estimated as the periodogram of $x_k[m]$, which is the Fourier transform of $\widehat{r}_x[l]$, given by

$$P_{x_k}(\omega) = \sum_{l=-M+1}^{M-1} \widehat{r}_{x_k}[l]\, e^{-jl\omega}, \tag{3}$$

where the angular frequency $\omega = 2\pi f$.

Since attenuation and backscatter intensity can be assumed to depend on the mass fraction of particles, studying $P_x(\omega)$ as a function of depth and settling time should give an indication of changes in local particle mass fractions. Hence, for each window position k, we estimate the PSD as above. For each depth, the PSD is then integrated over the bandwidth of the pulse, in this case defined by upper and lower frequency when the PSD has dropped -6 dB from the peak (center frequency). This integration reduces the data set from a three-dimensional set (depth, settling-time, and ultrasound frequency) to a two-dimensional set (depth and settling-time).

4. Results

Fig. 3 shows the energy of the backscattered sound as a function of depth and settling-time, for solids fractions of 1.7 vol%, 4.0 vol%, and 6.7 vol%. The results show that the slope of the ridge seen in the figure changes with total solids concentration, supporting the hypothesis that particles in dilute suspensions settle faster than in suspensions with higher solids fraction. We can also see a settling interface towards the end of the measurement, indicating there is a layer of solids at the bottom of the flow channel. Fig. 4 shows slices of Fig. 3, taken at five time instants

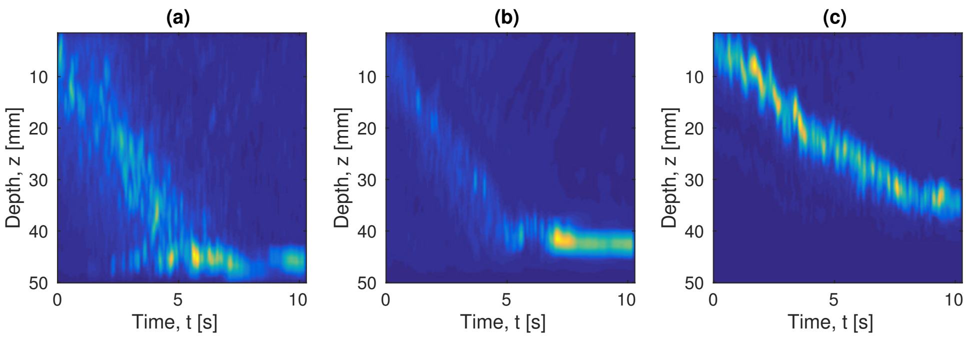

Fig. 3. Energy of backscattered ultrasound as function of the settling time, t for solids concentrations of (a) 1.7 vol%, (b) 4.0 vol%, and (c) 6.7 vol%.

after the pump was stopped, again for three solids concentrations. The curves in the figure show the distribution of backscattered energy as a function of depth, normalized so that the distributions integrate to unity (for the sake of clarity in the plots).

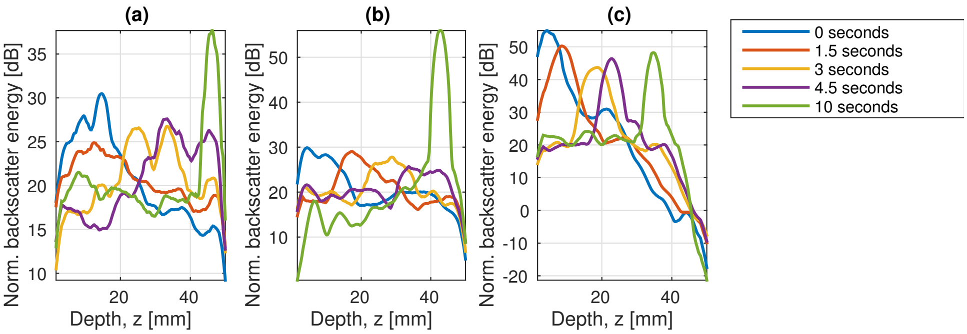

Fig. 4. Slices from Fig. 3, taken 0 s, 1.5 s, 3 s, 4.5 s, and 10 s after the settling process started, for solids concentrations of (a) 1.7 vol%, (b) 4.0 vol%, and (c) 6.7 vol%

5. Conclusions

In this paper, it is shown that the Power Spectral Density (PSD) of the signal is significantly affected by the mass fraction solids. By using the described method it is possible to qualitatively follow variations in local particle concentrations, as a function of depth and time, for suspensions with a wide range of particle mass fractions.

In a settling suspension it is possible to follow the settling interface. As shown, the settling velocity varies with particle concentration.

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