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Concentration Profiling using a Novel Acoustic Backscatter System with Single Transducers Pulsed at Multiple Frequencies

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Acoustic backscatter systems offer a flexible technique to measure dispersion concentration and particle size, through inversion of the return echo voltage response of pulse-echo signals in the MHz range. This study explores the use of the ultrasound array research platform to measure the suspended particle attenuation constant using acoustic backscatter from glass species, and invert the voltage response to produce concentration profiles. The measurement principle is described and experimentally determined values for the particle attenuation constant are compared to theoretical values from literature. Transducer constants for each probe are determined allowing concentration profiles to be inverted from the voltage profiles, and the limits for determining the attenuation constant are explored.

Keywords— acoustic backscatter, solids concentration measurement

I. Introduction

The projected lifetime cost of decommissioning the Sellafield nuclear site in the UK was ~£67.5bn in 2012, based on a report by the UK National Audit Office [1]. This legacy is due, in part, to the large cost for storage and processing of waste sludges, because of the high risk of radiological or toxicological contamination making characterization difficult or costly. For this reason, much research has been directed towards developing technologies for the remote characterization of nuclear waste for cleanup processes [2] [3]. Acoustic backscatter systems (ABS) represent such a technology, as they can be used non-intrusively to measure both particle size and concentration depending on prior system knowledge [4].

In this study, a calibration method, developed by Rice et al. [5] was used in order to find the attenuation constant, χ, so that backscatter voltage response could be inverted to produce concentration profiles and the value of χ obtained compared to that predicted by the Betteridge et al. [6] model. Although there have been recent developments in how acoustic backscatter (ABS) models can be broadened [7], from current applications in marine environments for measuring sediment flows, there is little data available for the Rayleigh regime (micron sized particles insonified at MHz frequencies) as the Thorne concentration inversion model is not applicable for colloidal particles that attenuate to a significant degree [4]. Developing these models so that backscatter concentration inversion can be applied to engineering systems would therefore be invaluable for systems where non-intrusive measurement is required.

II. Measurement Principle

The following model, ignoring multiple scatter effects, is described by Thorne and Hanes [4] where the root-mean-square of the received voltage, V, varies with distance from the transducer face, r, as given in (1).

$$\boldsymbol{V(r) = \frac{k_t k_s M^{\frac{1}{2}}}{r\psi} e^{-2r(\alpha_w+\alpha_s)}} \qquad (1)$$

where M is the mass concentration in kg/m^3, ψ is the near field correction factor (assumed to be unity in the far field region), a_w is the attenuation due to water for zero salinity given by Ainsley and McColm [8] as a function of frequency and temperature. a_s is the attenuation due to the sediment, k_t is the transducer constant, which depends on the system and is determined experimentally, and k_s is the particle species backscatter coefficient given by (2).

$$\boldsymbol{k_s = \frac{\langle f \rangle}{\sqrt{a\rho_s}}} \qquad (2)$$

where a is the particle radius, ρ_s is the particle density and f is the form function (angled brackets indicate an average over the particle size distribution). f determines the extent to which particles backscatter based on the insonification frequency and suspended particle size, and is based on the model by

Betteridge et al. [6] using experimental data for quartz sand sediments, as follows in (3), (4) and (5).

$$f = \frac{\varsigma x^2}{1.17 + 0.95x^2} \quad (3)$$

$$\varsigma = (1 - 0.5e^{-\left(\frac{x-1.5}{0.5}\right)^2})(1 + 0.4e^{-\left(\frac{x-1.5}{3.0}\right)^2})(1 - 0.5e^{-\left(\frac{x-5.9}{0.7}\right)^2}) \quad (4)$$

$$\mathbf{x = k.a} \quad (5)$$

where k is the acoustic wavenumber (meter^{-1}). The attenuation constant, a_s is defined and calculated, as is given by Thorne and Hanes [4] in (6) and (7).

$$\alpha_s = \frac{1}{r}\int_0^r \xi(r')M(r')dr \quad , \quad \xi = \frac{3\langle\chi\rangle}{4\langle a\rangle\rho_s} \quad (6, 7)$$

where ξ is known as the sediment attenuation constant in m^2 kg^{-1}, χ is the normalized total scattering cross-section. χ was also modelled based on the insonification frequency and particle radius by Betteridge et al. [6] as shown in (8) and (9).

$$\chi = \frac{0.24\varphi x^4}{0.7 + 0.3x + 2.1x^2 - 0.7x^3 + 0.3x^4} \quad (8)$$

$$\varphi = 1 - 0.4e^{-\left(\frac{x-5.5}{2.5}\right)^2} \quad (9)$$

in order to be able to determine the attenuation constant in arbitrary suspensions, Rice et al. [5] linearized (1) with respect to the attenuation coefficients by taking the natural logarithm of both sides to produce the G-function as shown in (10).

$$G = \ln(\psi r V_{rms}) = \ln(k_s k_t) + \frac{1}{2}lnM - 2r(a_w + a_s) \quad (10)$$

if particle concentration, M, does not change with distance, r (such that the subscript h indicates a homogenously mixed system) defining a_{sh} as in (11), by taking the derivative with respect to r we obtain (12).

$$\alpha_{sh} = \xi_h M \quad , \quad \frac{\partial G}{\partial r} = -2(\alpha_w + \xi_h M) \quad (11, 12)$$

Differentiating (12) with respect to the mass concentration produces (13). Essentially, (13) allows the simple calculation of the attenuation constant, by first taking the linear gradient, as the differential of G wrt distance, r, and then the gradient of dG/dr wrt concentration, M,

$$\xi_h = -\frac{1}{2}\frac{\partial^2 G}{\partial M \partial r} \quad (13)$$

With all constants measured or estimated (1) can be inverted to allow calculation of concentration profiles for particles of a particular size. If only one frequency is available, in order to obtain a concentration profile, an estimate must be made for a_s to allow k_s and ξ to be calculated. If M.ξ << 1 then α_s can be assumed to be zero yielding the relationship shown in (14). If it cannot be assumed that α_s = 0 then an iterative approach is used. The first calculation is performed assuming α_s = 0 the result of which is fed in to (15) to predict a new value for M [4].

$$M_0 = \left\{\frac{V_{rms}\psi r}{k_s k_t}\right\}^2 e^{4r\alpha_w} \quad , \quad M_1 = M_0 e^{4r\alpha_s} \quad (14, 15)$$

where a_s is obtained using the newly found M_0 profile. This process is repeated until M_n and M_{n+1} are convergent, allowing a concentration profile to be produced, calculated for each value of distance r. This approach has been used previously [9], but caution must be used as the iterative feedback between M and a_s is positive and can cause the solution to diverge to zero or infinity due to feedback errors as the distance from the transducer increases [4].

III. Materials and Methodology

TABLE I. Materials used in this Study

Material Name	Manufacturer	Particle d_{50} (μm)
Honite-22	Guyson	45.5
Honite-16	Guyson	78.6
Honite-12	Guyson	173.4

Three size fractions of spherical glass beads were used in this study as the test material, with details shown in Table I. Particle d_{50} was measured using a Malvern Mastersizer 2000T.

The Ultrasound Array Research Platform (UARP) II, developed at the University of Leeds [10], was used to collect ABS data throughout this study. It features 16 channels to allow for multiple probes to be used with individually set frequencies up to 15 MHz and is operated using Matlab based software. All raw data is archived for offline processing and real time data is shown for operator feedback [10] [11].

Measurements were taken in an impeller-agitated, 1 m tall, 0.3 m wide calibration tank over a 0.3 m range using eight Olympus transducers (Olympus NDT V323, 0.25-inch active diameter) arranged radially from the center of the tank facing perpendicular to the base pulsed at frequencies of 2, 2.25 and 2.5 MHz for eight particle concentrations ranging from 2.5 to 133.7 kg m^{-3}. The excitation duration for the transducer was 10 μs and echo voltage response was recorded from 31172 points spaced over the 0.3 m range averaged over 10,000 measurements with each profile taking ~5 minutes to measure. Suspension samples were taken at multiple depths simultaneously using a five-headed pump and particle concentration determined gravimetrically. A second pump was also used to redistribute suspension from the conical base of the tank to the top to prevent particles from settling out and ensure homogeneity.

IV. Results and Discussion

As an example of the raw profile data measured with the UARP, Fig. 1 displays the averaged voltage strength (in dB) versus distance from the transducer, for Honite-16 dispersions at four concentrations, measured with the central transducer frequency (2.25 MHz). It can be seen from Fig. 1, that once outside of the near field region (within the first ~0.05 m), a logarithmic decay in the decibel level with distance is

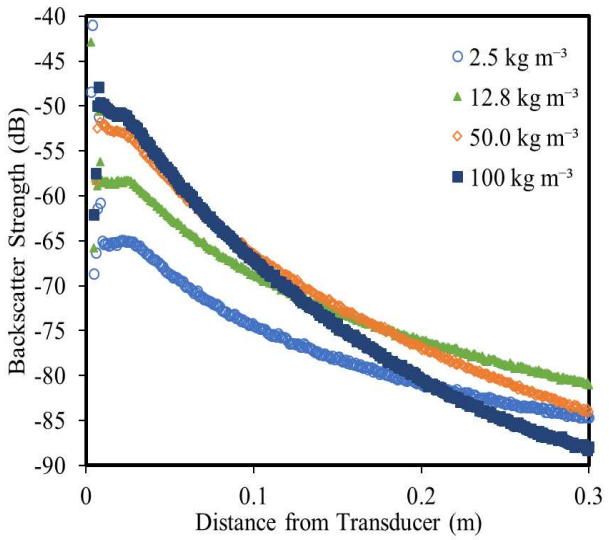

Fig. 1. Decibel profiles for Honite-16 at 2.25 MHz (single probe)

observed, typical of moderately attenuating suspensions where both attenuation and scattering parameters affect backscatter strength, leading to the relationship observed.

The backscatter voltages were converted to G-function values using (10) and are shown again with respect to distance for the same systems in Fig. 2. It is observed that the G-function is linear with respect to distance outside of the near field region (first ~0.05 m), although there is a slight deviation from linearity at greater distances for higher particle concentrations as the voltage drops towards the noise floor of the instrument (-90 dB, ~ -11.5 G-function value). dG/dr values, were determined by taking the gradient of the G-function profile over 0.1 – 0.25 m, while still ensuring that a linear fit was appropriate. Average dG/dr values versus concentration are shown for all three frequencies (2, 2.2.5 and 2.5 MHz) from the Honite-16 dispersions in Fig. 3.

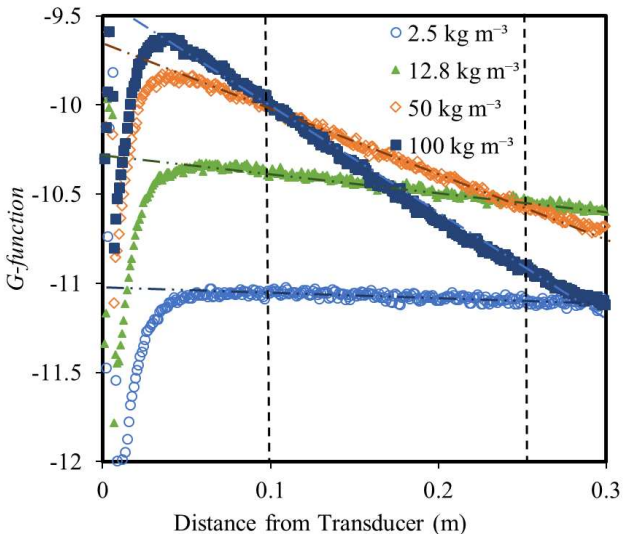

Fig. 2. G-function profiles for Honite-16 at 2.25 MHz (single probe). Dashed lines represent linear interpolations over a 0.1 – 0.25 m distance.

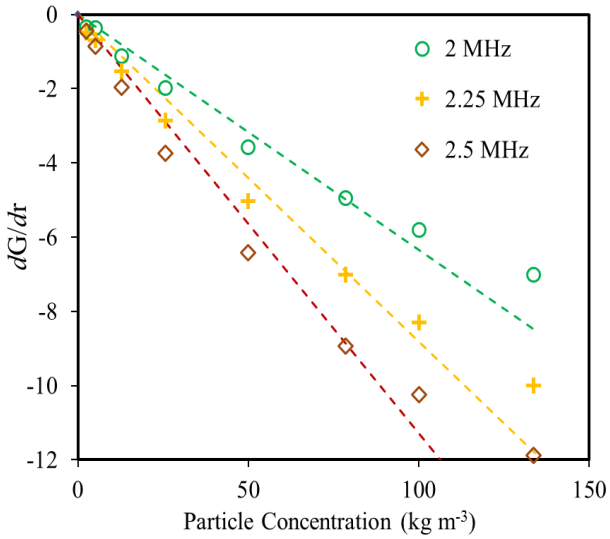

Fig. 3. Gradient of G profiles wrt distance, r, plotted against concentration for Honite-16 at 2.25 MHz (single probe)

It can be observed in Fig. 3 that a linear fit is adequate up to ~75 kg m^{-3}, which is consistent with the theoretical interpretation described in Section II. However, the dG/dr values begin to plateau for Honite-16 above this value, and this same plateau was evident at even lower concentrations (50 kg m^{-3}) for the larger glass species, Honite-12 (not shown here). It is assumed this deviation occurs as the correlation between attenuation and concentration becomes non-linear at high particle loadings, and indicates a previously unrecorded limit to which this calibration procedure can be applied.

By plotting the dG/dr values against the concentration at which they were measured (as shown in Fig. 3), taking the gradient of the line produced and substituting it into (13), a value for ξ_h can be determined for each frequency and particle size. The transducer constant k_t can then be calculated by first estimating k_s using (2), (3), (4) and (5) and rearranging (1) for

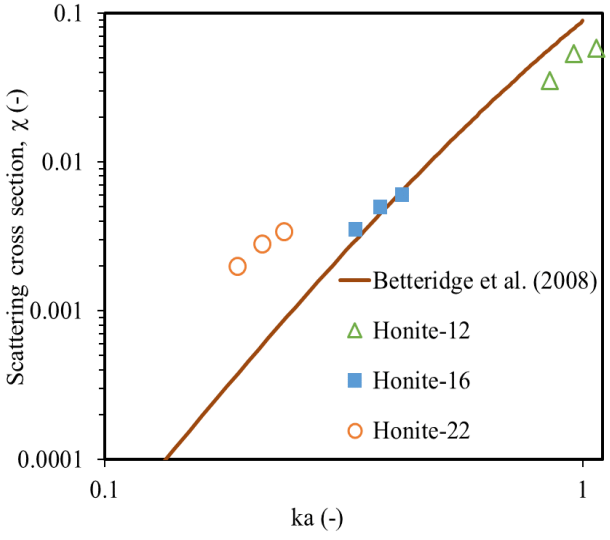

Fig. 4. Experimentally determined values of χ compared with values predicted by Betteridge et al. [6] model

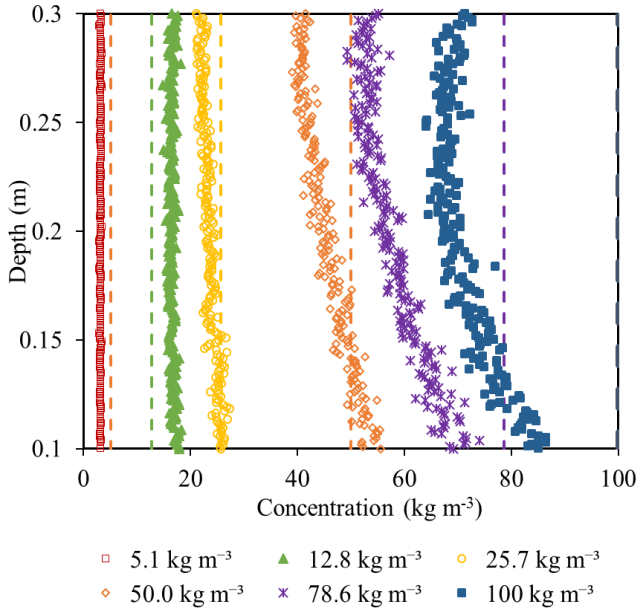

Fig. 5. Backscatter concentration profiles produced from voltage profiles using experimentally determined value of χ for Honite-16 at 2.25 MHz (single probe)

k_t using the experimental values of ξ. Intermediate particle concentrations were used (2.5 – 12.8 kg m^{-3}) as it has been found to produce less variability in the values of k_t [6]. Average transducer constants determined for the Olympus probes from this method were found to be ~2×10^{-5}.

With values of the attenuation and transducer constants determined, overall values of the dimensionless function χ could be calculated using (7). Fig. 4 shows experimental values of χ compared to those predicted by the Betteridge et al. [6] model using (8) and (9). Experimental results fit well for $ka > 0.5$ but deviate by an order of magnitude below this value. This result may be due to the viscous attenuation (which becomes dominant for $ka < 1$) being neglected in the Betteridge et al. [6] model. The influence of viscous attenuation has been discussed by Thorne and MacDonald [7] who predicted a decrease in χ for $0.1 < ka < 1$ while gradually increasing for $10^{-2} < ka < 0.1$. Their predictions been used succesfully by Sahin et al. [12] to measure flocs comprised of small (~ 9 µm) sediment particles. Furthermore, due to lower particle scattering and attenuation at lower ka values, instrument sensitivity and an increasingly dominant solvent attenuation term can cause difficulties in obtaining an accurate value for χ.

Fig. 5 shows backscatter-inversion concentration profiles produced for Honite-16 at 2.25 MHz for 0.1 – 0.3 m range (14,15). It is observed that, although the inversion is fairly accurate up to 50 kg m^{-3}, above this value it begins to significantly under-predict true concentrations. One likely cause of these discrepancies is that multiple scattering is enhanced at intermediate to high concentrations leading to a lower backscatter voltage strength than predicted by (1). It is noted that concentrations used are far above the 2.5 kg m^{-3} limit for multiple scattering prescribed by Betteridge et al. [6], but are close particle levels associated with a reduction in backscatter strength for 2.25 MHz probes measured previously [13].

V. Conclusions

This paper has demonstrated the ability of ABS systems to be calibrated accurately for arbitrary suspensions using the G-function approach of Rice et al. [8] and explored the limits of such a calibration for both sediment concentration and the value of ka. Successful concentration inversion of ABS profiles at high particle loading has demonstrated the ability of such systems to be used in engineering applications such as the nuclear industry where radiochemical hazards make sampling and other offline techniques hazardous.

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