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Development of a real-time acoustic backscatter system for solids concentration measurement during nuclear waste cleanup

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***Abstract*— The measurement of the concentration of solid particles in suspension without physical sampling is a necessary tool for the nuclear industry involved with cleanup of a significant quantity of legacy waste in the form of sludge. This paper presents the work of a project to develop acoustic instrumentation for the *in-situ* characterization of such sludge. The measurement principle and signal processing employed is presented along with the design of a custom acoustic instrument for deployment in nuclear and industrial environments. The paper presents experimental results demonstrating the ability of the technique for the online measurement of mass concentration in a suspension of glass power in water.**

Keywords—acoutsic backscatter, ABS, solids concentration measurement, in-situ characterisation, industrial measurement

I. INTRODUCTION

The UK civil nuclear industry has a large, diverse waste inventory that requires processing and disposal [1] representing the UKs highest nuclear contamination risk, the removal of which is of national importance. The cleanup project lifetime cost was estimated at £67.9 billion in 2012 [2]. There is a lack of characterization of these sludges due to the inherent high radiological and toxicological risks encountered during sampling and laboratory analysis.

This work aims to address the lack of suitable online measurement systems for real time characterization of suspended solids in sludges and slurries to aid the development of new nuclear waste processing procedures. Additionally this work is applicable to process control in the chemical, mining, minerals and waste water engineering industries where improved real-time measurement may allow improvements in efficiency to be realized.

Previous work on establishing the concentration of solids suspended in a liquid using acoustic backscatter (ABS) has stemmed from the study of natural system: colloidal suspensions [3] and marine processes [4].

II. MEASUREMENT PRINCIPLE

Thorne and Hanes derived an expression of the instantaneous voltage of a received back scattered echo received at a single transducer due to a mass concentration, M_w, of suspended particles as [4]:

$$V_{\mathrm{rms}} = \frac{k_s k_t}{\psi r} M_W{}^{\frac{1}{2}} e^{-2r(\alpha_w+\alpha_s)} \qquad (1)$$

where r is distance from the transducer face, $k_s$is a particle species dependent backscatter co-efficient,

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

k_t, is the transducer constant, a system dependent parameter, ψ, a near field correction factor,

$$\psi = \frac{1+1.35z+(2.5z)^{3.2}}{1.35z+(2.5z)^{3.2}} \qquad (3)$$

and $\alpha_w$and $\alpha_s$are the attenuation of water and the suspended particles respectively. Rice et all devised a method to determine the attenuation constant from the range and near field compensated echo amplitude, G, as [5]:

$$G = \ln(\psi r V_{\mathrm{rms}}) = \ln(k_{sh} k_t) + \frac{1}{2}\ln M_W - 2r(\alpha_w + \alpha_{sh}) \qquad (4)$$

Taking the derivative of G with respect to distance, r, allows the definition of an equation free from system parameters

$$\frac{\partial G}{\partial r} = -2(\alpha_w + \alpha_{sh}) \qquad (5)$$

where the attenuation constant of water, α_w, at a frequency, f, and temperature, T, is defined as:

$$\alpha_w = 0.05641 f^2 e^{\left(-\frac{T}{27}\right)} \quad (6)$$

and particle scattering constant, α_{sh}, as:

$$\alpha_{sh} = \xi_h M_W \quad (7)$$

where the material dependent constant, ξ_h, forms the relationship between attenuation and mass concentration of a homogeneous suspension.

This study is based on exploiting the calculation of $\partial G/\partial r$, and hence, ξ_h, as a route to real-time in-situ measurement of the mass concentration of an aqueous suspension.

III. Hardware Design

As a part of this work, a custom ultrasound instrumentation system was developed, tailored to the technical requirements of deployment in a real world nuclear or industrial environment as shown in Figure 1.

Primarily the instrument is designed to perform real-time online measurement where material properties change both with space and time. Spatial material characterization is performed through the use of sixteen transmit-receive channels, connected to an array discrete transducers. In order to achieve *real-time* measurement and reduce the time averaging effects inherent with a technique requiring the root mean square of multiple measurements, high speed measurement is a necessity. The use of multiplexers, although allowing significant simplification of the instrument design, imposes a time penalty on measurement. Instead, the instrument was designed with sixteen independently controllable transmit-receive channels. The data path within the instrument is pipelined such that whilst a measurement is in progress, received data is stored in local memory in real-time, concurrently data from previous measurements may be accessed and downloaded from the instrument for analysis on a PC. As such the rate at which measurements are made is determined by the physical properties of the measurement and process (e.g. transit time of the ultrasound wave) rather than by instrument limitations.

The transmit circuitry of each channel is based on the Maxim Integrated MAX14808 integrated circuit (IC) configured for five level switched mode excitation at up to ±100 volts at 2 amps with integrated T/R switch. Excitation waveform characteristics are controlled through precise timing of the transitions between switched voltage levels allowing cancellation of harmonics [6], precise amplitude control [7] and synthesis of arbitrary waveforms [8].

The receive circuitry is based on the Texas Instruments AFE5808 IC providing a 12, 18 or 24 dB low noise amplifier (LNA), 40 dB of programmable gain amplifier (PGA) for time gain compensation (TGC) and 24 or 30 dB of programmable gain amplifier (PGA), totaling up to 54 dB of amplification. Additionally low pass filters can be programmed to 10, 15, 20, or 30 MHz cutoff frequency. Analog to digital conversion (ADC) is performed at 12 bits at a sampling frequency of 80 MSPS, resulting in a data rate of 0.96 Gbps per channel, or 15.36 Gbps total.

Fig. 1. Custom built, industrially deployable, sixteen channel ultrasound array research platform (UARP) for the characterisation of suspensions through acoustic backscatter (ABS) analysis.

Received data is initially stored in on-chip memory with an Altera Stratix V FPGA (5SGSMD5K2F40C2N) where programmable delays may be applied to store the desired receive window according to the sequencing scheme. Subsequently, data is stored in 512 MB of dedicated onboard DDR3 memory.

Communications between the control and analysis computer and the instrument is performed using a PCIe copper or optical fiber link at any configuration up to Gen 3, eight lanes (Nominal 64Gbps link rate). The optical fiber configuration allows deployment of the instrument at up to 300 meter separation from the operator and control and analysis computer. The instrument is controlled via command line or graphical user interface from the Matlab environment, or customized software accessing the communications drivers.

For safety in high risk environments, the instrument is powered from an 110V center-taped supply (55V-0V-55V) and the excitation power supplies are remotely controlled and only active during measurements.

IV. Experimental Investigation

In order to verify the use of $\partial G/\partial r$ as a method of measuring mass concentration, M_W, of a program of characterizing a series of well-defined suspensions has been undertaken. A spherical glass power, Honnite-16, was chosen for its mono-disperse particle size characteristics and suspensions of know mass concentrations between 1 and 64 kg/m^3. In order to counteract settling of the particles and create a homogeneous suspension, a doubly mixed approach was utilized. Firstly, a triple rotating impeller mixes the suspension, whilst to ensure even mixing, the whole tank is continuously rotated anticlockwise. A fixed baffle was employed to prevent the formation of vortices, and buoyant hollow plastic spheres on the surface further reduce the entrainment of air bubbles into the suspension as shown in Figure 2.

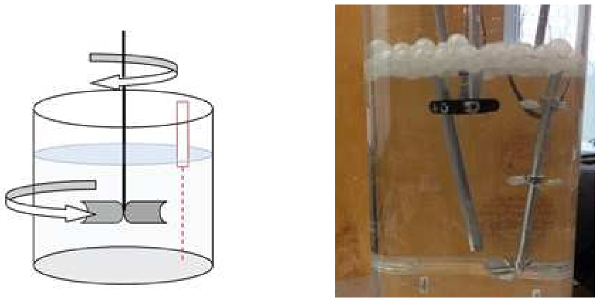

Fig. 2. Schematic diagram of the experimental setup for cnducting acoustic backscatter measurments on homogenious suspensions (left) and a photograph of showing actual setup (right).

An immersion transducer of 2.25 MHz central frequency and 0.25inch active element diameter (Olympus NDT V323) was connected to the instrument via an 8 meter RG174 coaxial cable of 50 Ω characteristic impedance. The transducer was arranged pointing down into the suspension from the top of the test tank. The transducer was consecutively excited with three different waveforms of frequency 2.00, 2.25 and 2.50 MHz, of duration 10 µs and ±100V and Hann windowing. The waveforms were encoded as using five discrete voltage levels [7]. In total 10,000 received waveforms were collected for each excitation waveform and sored for post-processing.

V. Results and Discussion

The 10,000 back scattered echo signals received for each mass concentration of suspension was processed within Matlab to produce the root mean square echo amplitude for each time sample. The resulting echo amplitude waveforms for a 2.25 MHz excitation frequency are plotted versus distance from the transducer in Figure 3. A decibel scale is used to allow visualization of this widely variable dataset. The excitation waveform is seen in the 0.02 meters of the backscatter response and a strong echo from the base of the tank is found at 0.23 meters.

Examination of the dataset shows an overall increase in the backscatter echo amplitude versus distance from the transducer for concentrations up to 16 kg/m^3, however at higher concentrations this trend is less obvious. Echo amplified alone cannot be used to measure concentration.

The natural logarithm of the distance normalized and near field corrected echo amplitudes of each suspension generated the G value. The resulting waveforms for a 2.25 MHz excitation frequency are shown in figure 4. For each waveform the average value of $\partial G/\partial r$ between 0.1 and 0.2 meters was calculated. The average value of $\partial G/\partial r$ is plotted against mass concentration, M_w, for excitation frequencies of 2.0, 2.25 and 2.50 MHz in figure 5. The linear trend in $\partial G/\partial r$ versus M_w is plotted for each excitation frequency, the slope of which yields ξ_h, as shown in table 1.

Variances in the values of $\partial G/\partial r$ from the linear fit are attributed to the difficulty in suspending particles to produce a homogeneous suspension, and may be reduced by comparing data from multiple different test tank designs each with varying mixing strategies.

Calculating $\partial G/\partial r$ from the backscatter echo response from a suspension of unknown mass concentration, provided that ξ_h.has been previously established for the material may now yield a measurement of the mass concentration without the need for sampling and laboratory analysis.

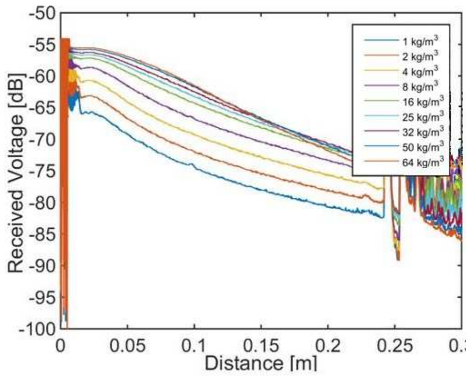

Fig. 3. RMS voltage of 10,000 received backscatter signals in decibels versus distance from the ultrasound transducer, r, for respective mass concentrations of Honite-16 glass powder for 2.25 MHz tone excitation.

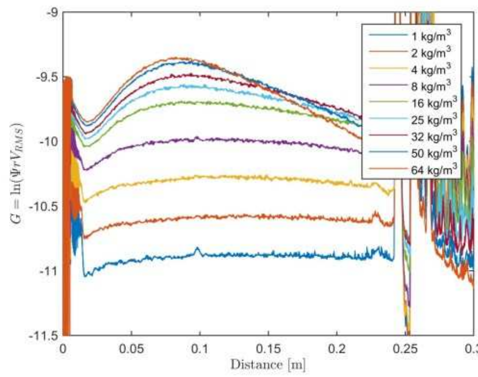

Fig. 4. G versus distance from the ultrasound transducer, r, for respective mass concentrations of Honite-16 glass powder for 2.25 MHz tone excitation based on 10,000 waveform measurments.

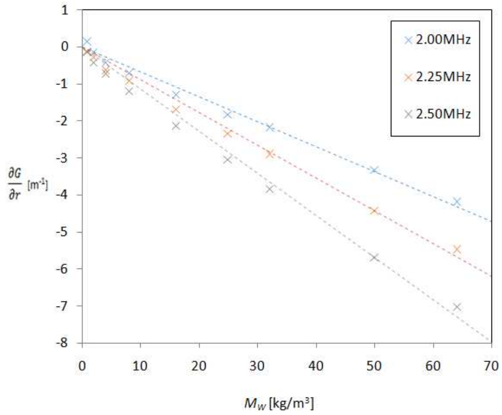

Fig. 5. Plots of attained average values of $\partial G/\partial r$ versus M_w to yield values of ξ_h for the different frequencies tested for Honite-16.

Frequency (MHz)	$\boldsymbol{\xi_h}$ ($kg^{-1}m^2$)
2.00	0.0337
2.25	0.0435
2.50	0.0570

Tab. 1. Summary of calculated *ka* vaues and measured values of ζ_h for excitation frequencies of 2.00, 2.25 and 2.50 MHz for suspensions of Honite-16 spherical glass particles in water.

VI. Conclusions

This paper has presented the design of instrumentation for the measurement of mass concentration of solid particles in suspension through the characterization of the backscattered echo signal. This technique is specifically targeted at the cleanup of legacy nuclear waste in a bid to reduce the need to physical sampling and laboratory analysis but is of equal significance to the process and manufacturing industries, minerals and mining and waste water treatment.

The method has the added benefit of overcoming variances in sensitivity between transducers and with time by differentiating the received echo signals against distance. This is of particular importance in long term installations where transducer sensitivity may degrade with time, or transducers may be replaced due to physical wear or damage.

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