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Modelling acoustic scattering by suspended flocculating sediments

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ABSTRACT

The development of a theoretical description of how sound interacts with flocculating sediments has been lacking and this deficiency has impeded sound being used to extract quantitative suspended sediment parameters in suspensions containing flocs. As a step towards theoretically examining this problem a relatively simple heuristic approach has been adopted to provide a description of the interaction of sound with suspensions that undergo flocculation. A model is presented for the interpretation of acoustic scattering from suspensions of fine sediments as they transition from primary particles, through an intermediate regime, to the case where low density flocs dominate the acoustic scattering. The approach is based on modified spherical elastic solid and elastic fluid scatterers and a combination of both. To evaluate the model the variation of density and compressional velocity within the flocs as they form and grow in size is required. The density can be estimated from previous studies; however, the velocity is unknown and is formulated here using a fluid mixture approach. Uncertainties in these parameters can have a significant effect on the predicted scattering characteristics and are therefore investigated in the present study. Furthermore, to assess the proposed model, outputs are compared with recently published laboratory observations of acoustic scattering by flocculating cohesive suspensions.

1. Introduction

The transport of sediments in coastal and estuarine waters is important because of the impact it has on aquatic habitats, water quality, turbidity, biogeochemistry and morphology (Amoudry and Souza, 2011). Developing capabilities to monitor and model marine sediment transport is therefore an essential component of coastal management (Davies and Thorne, 2008). To facilitate these developments new technologies are continually being investigated and acoustics is one of the techniques being used to advance our measurement capabilities (Thorne and Hay, 2012). Acoustics is being developed for sediment transport process studies because it is recognised as having the capability of measuring non-intrusively, co-located, simultaneously and with high spatial-temporal resolution, suspended sediment (Pedocchi and Garcia, 2012) and flow profiles (Hurther and Thorne 2011) and provide information on bedforms (Hay, 2011).

The use of acoustics in non-cohesive inorganic sedimentary environments has been very successful, with many studies utilising sound to examine sediment transport processes over sandy beds (Hay et al., 2012; O'Hara Murray et al., 2012; Bolanos et al., 2012; Chassagneux and Hurther, 2014). In particular the acoustic approach has been successfully applied to the measurement of suspended sediments (Hay and Bowen, 1994; Thorne et al., 2009; O'Hara Murray et al., 2011). Apart from the technology developments, the success of the use of sound for suspension measurements has been due to an evolving description of the acoustic scattering properties of irregularly shaped sandy particles (Hay, 1991; Thorne and Meral, 2008; Moate and Thorne, 2013) and the development of inversion methodologies to extract suspension parameters from the backscattered sound (Crawford and Hay, 1993; Thosteson and Hanes, 1998; Hurther et al., 2011; Moore et al. 2013; Thorne and Hurther, 2014). This has led to the development of multi-frequency acoustic backscatter systems becoming available as commercial products for suspended sediment studies and these are being utilised by the coastal and estuarine community.

Although acoustics has had success in measuring suspended sediments in regions predominantly composed of non-cohesive sandy sediments, its application in the regime of fine grained sediments, usually considered to be silts and clays, has been more problematic (Gartner, 2004; Ha et al., 2009, 2011; Sahin et al., 2013). When acoustic systems are used in studies on fine grained sediment transport, it is usually in combination with in-situ samples to calibrate and quantify the acoustic measurements (Shi et al., 1999; Holdaway et al.; 1999; Fugate and Friedrichs, 2002; Moore et al., 2012), however, it is generally acknowledged

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Nomenclature

a	Particle radius (m)
a_o	Mean radius based on n(a) (m)
c_w	Sound velocity in water (m s^{-1})
c_f	Sound velocity in a fluid scatterer (m s^{-1})
c_s	Sound velocity in the primary particles (m s^{-1})
C_f	Effective density flocculation constant (kg m$^{(3-m)}$)
f	Intrinsic backscatter form function (dimensionless)
f_{ss}	Intrinsic backscatter form function for a solid elastic sphere (dimensionless)
f_{si}	Intrinsic backscatter form function for an irregularly shaped solid elastic particle (dimensionless)
f_{fs}	Intrinsic backscatter form function for a fluid elastic sphere (dimensionless)
f_{fi}	Intrinsic backscatter form function for an irregularly shaped fluid elastic scatterer (dimensionless)
f_h	Intrinsic hybrid backscatter form function for a scatter of variable density (dimensionless)
f_o	Ensemble backscatter form function (dimensionless)
f_{ho}	Ensemble hybrid backscatter form function for a scatter of variable density (dimensionless)
k	Acoustic wavenumber, $2\pi/\lambda$ (m^{-1})
K	Sediment backscattering property (kg$^{-1/2}$ m)
m	Exponent to which the particle size is raised to parameterise flocculation
M	The suspended concentration (kg m^{-3})
$n(a)$	Particle number radius probability density function (dimensionless)
N	Number of particles per m^3 (m^{-3})
r	Range from the transducer (m)
$\mathfrak{R}$	The system constant (V m$^{3/2}$)
V	Root-mean-square backscattered signal (V)
x	ka (dimensionless), $x_o = ka_o$ (dimensionless)
α_w	Attenuation due to water absorption (Nepers m^{-1})
α_s	Attenuation due to sediment scattering and viscous absorption (Nepers m^{-1})
γ	Normalised density of the scatter relative to the density of water (dimensionless)
γ_o	Minimum normalised density of the scatter relative to the density of water (dimensionless)
δ	Normalised standard deviation σ/a_o of n(a) (dimensionless)
ε	Fluid heuristic formulation coefficients (dimensionless)
ζ	Normalised sound velocity of the scatter relative to the sound velocity in water (dimensionless)
ζ_o	Minimum normalised sound velocity of the scatter relative to the sound velocity in water (dimensionless)
κ_w	Compressibility of water (Pa)
κ_s	Compressibility of the solid primary particles (Pa)
λ	Wavelength of sound (m)
υ	Kinematic viscosity (m^2 s^{-1})
ξ	Sediment attenuation constant (kg^{-1} m^2)
ρ_w	Density of water (kg m^{-3})
ρ	Density of the suspended scatterers (kg m^{-3})
ρ_s	Density of the solid primary particles (kg m^{-3})
ρ_f	Density of a fluid scatterer (kg m^{-3})
ρ_o	Minimum density of the suspended scatterers (kg m^{-3})
ρ_e	Effective density of the suspended scatterers (kg m^{-3})
σ	Standard deviation of $n(a)$ (m)
φ	Porosity of the suspended scatterer
χ	Intrinsic normalised total scattering cross-section (dimensionless)
χ_{ss}	Intrinsic normalised total scattering cross-section for a solid elastic sphere (dimensionless)
χ_{sv}	Intrinsic normalised total scattering cross-section for the viscous attenuation of a solid elastic sphere (dimensionless)
χ_{fs}	Intrinsic normalised total scattering cross-section for a fluid elastic sphere (dimensionless)
χ_{si}	Intrinsic normalised total scattering cross-section for an irregularly shaped solid elastic particle (dimensionless)
χ_{fi}	Intrinsic normalised total scattering cross-section for an irregularly shaped fluid elastic scatterer (dimensionless)
χ_h	Intrinsic hybrid normalised total cross-section for a scatter of variable density (dimensionless)
χ_o	Ensemble normalised total scattering cross-section (dimensionless)
χ_{ho}	Ensemble hybrid normalised total cross-section for a scatter of variable density (dimensionless)
ψ	Transducer nearfield correction term (dimensionless)
ω	Angular acoustic frequency (s^{-1})

that if the process of flocculation occurs during the measurement campaign, interpretation of the acoustic observations are challenging and uncertain. The main reason for this uncertainty arises because there has been neither measurements collected on the interaction of sound with flocculating sediments under controlled conditions, nor the development of a theoretical framework to describe such interactions. Therefore the use of multi-frequency acoustic backscatter systems to study sediment transport processes in cohesive fine grained environments is much less developed than that in the non-cohesive sandy regime.

To expand the quantitative use of acoustics, from non-cohesive sediments, to fine grained cohesive flocculating environments, a recent experimental study (MacDonald et al., 2013) was carried out. In a series of acoustic backscatter measurements on suspensions of fine grained primary particles, of which flocs are composed, and, through the addition of a flocculating agent, on flocs formed by the aggregation of the primary particles, controlled acoustic observations were made on the interaction of sound with a suspension of flocculating sediments. As a complementary study to the experimental work, developments to model the observations have been in progress (Thorne et al., 2012a, 2012b) and the result is reported here.

The methodology adopted for the flocculating scattering model is comparable to the heuristics approaches used in the description of non-cohesive sediment scattering (Hay, 1991; Schaafsma and Hay, 1997; Thorne and Meral, 2008; Moate and Thorne, 2009) and zooplankton scattering (Johnson, 1977; Stanton 1990; Wiebe et al., 1990; Stanton and Chu, 2000). The concept is to utilise the acoustic scattering characteristic of well understood bodies with analytical solutions, such as spheres and cylinders, to form the basis of the scattering description, and modify, and often simplify, the analytical expressions to obtain formulae which can be usefully applied to more asymmetric irregularly shaped scattering bodies. This approach is well developed and used successfully in acoustics (Stanton and Chu, 2000; Lawson et al., 2006; Thorne and Meral, 2008; Moate and Thorne, 2012). For the present study a modified solid elastic sphere is used to represent the scattering by primary particles and this has been validated with published data (Thorne and Meral, 2008). To represent the scattering characteristics of the somewhat nebulous collection of primary particles which compose a large low density floc, a single scattering body is proposed which has the combined acoustic properties of the water and the primary particles. A modified fluid elastic sphere model is used to