The effect of suspended particles on the performance of minehunting sonars in turbid coastal water

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Abstract

Future minehunting sonars will operate in the frequency range 50-300 kHz and over ranges of the order of several hundred metres. At these frequencies and ranges attenuation due to suspended particulate matter (SPM) in turbid coastal waters may have a significant impact on sonar performance.

Models for calculating the acoustic attenuation due to viscous absorption and scattering of sound by SPM are described. A method for including these effects into sonar performance models is discussed and results from a simple isovelocity, uniform bathymetry, single path, sonar equation model are presented which show that the detection range of a typical minehunting sonar may be significantly reduced by the presence of a suspension of quartz particles at moderate concentrations. Laboratory investigations of viscous absorption by SPM have also been carried out. These experiments are described, and the measurements are compared with the model predictions.

1. Introduction

Classically, efforts in sonar performance prediction modelling have concentrated on the low frequency, long range, anti-submarine warfare (ASW) scenarios in the deep ocean (so-called 'blue-water'), well away from coastal influences. Sonar applications in shallow, coastal waters employ relatively high frequencies, in the range 50 - 300 kHz, and operate over shorter ranges, of the order several hundred metres. Shallow coastal environments are characterised by high concentrations of suspended mineral particles relative to the open ocean, resulting from the action of rivers discharging into the sea or from the actions of waves and tidal currents stirring up bottom sediments. Previous calculations (Heathershaw et al. [1], Richards et al. [2]) have shown that such suspensions can lead to significant additional acoustic attenuation at high frequencies for quite moderate concentrations of order 0.1 kg m^{-3}. Concentrations of this level have been detected several tens of kilometres offshore in sediment plumes (e.g. South Atlantic offshore of the Amazon river [3], the Yellow Sea and the East China Sea offshore of the Yellow and Yangtze rivers [4]), and may easily be an order of magnitude greater in some river estuaries and in the beach surf zone.

2. Attenuation theory

Sound attenuation in seawater containing suspended particulate matter may be considered to be the sum of attenuation due to the clear seawater and the additional attenuation due to the suspended particles. Existing sonar performance models consider only the attenuation in clear seawater, neglecting the effects of the particles.

The sound intensity attenuation coefficient α is defined by the expression

$$I = I_0 e^{-2\alpha r} \tag{1}$$

where I_0 is the initial sound intensity and I is the intensity after propagation over range r. In this expression α is in units of Nepers m^{-1}, but units of dB m^{-1} will be used in the rest of this paper to be consistent with units used in sonar.

The attenuation coefficient in seawater containing suspended solid particles may be written

$$\alpha = \alpha_w + \alpha_v + \alpha_s \tag{2}$$

where α_w, α_v and α_s are the attenuation coefficients due to clear seawater, viscous absorption by suspended particles and scattering by suspended particles respectively. Simple expressions for the attenuation coefficients due to viscous absorption and scattering have been used in this work, and these are discussed below. These simple models have been validated by comparison with a more complete numerical model of the physical processes involved (Richards and Heathershaw [5]).

2.1. Attenuation in clear seawater

The absorption in clear seawater may be considered as the sum of absorption due to pure water, through volume and shear viscosity, and absorption due to two ionic relaxation mechanisms involving magnesium sulphate and boric acid. Absorption due to ionic relaxations involving other salts is negligible.

Several empirically derived expressions exist in the literature for calculating the acoustic attenuation coefficient of seawater (e.g. Thorpe [6], Schulkin and Marsh [7], Fisher and Simmons [8], Francois and Garrison [9, 10]). The one that appears to be the most complete for use at high frequencies is that of Francois & Garrison [9, 10], and it is their expression that has been used in this work.

2.2. Viscous absorption

Viscous absorption arises as a result of the density difference between the fluid and the solid particles. Since the particles are generally more dense than the fluid they have more inertia than an equivalent volume of fluid. This causes the oscillatory motion of the particles resulting from the incident sound field to lag behind that of the fluid, and there will therefore be a boundary layer in the fluid at the surface of each particle in which there is a velocity gradient. Since the fluid has a finite viscosity, this velocity gradient leads to frictional heat generation and hence loss of energy from the sound field.

Urick [11] derived an expression for the viscous absorption attenuation coefficient for spherical particles based on consideration of the expression for viscous drag developed by Stokes [12]. Urick's expression can be written

$$\alpha_v = (10 \log e^2) \left(\frac{\epsilon k (\sigma - 1)^2}{2} \left[\frac{s}{s^2 + (\sigma + \delta)^2} \right] \right) \quad \text{dB m}^{-1} \tag{3}$$

with

$$\delta = \frac{1}{2} \left[1 + \frac{9}{2\beta a} \right] \quad , \quad s = \frac{9}{4\beta a} \left[1 + \frac{1}{\beta a} \right] \tag{4}$$

where ϵ is the volume fraction of suspended material, $k = \omega/c$ is the wavenumber of the incident compression waves with c the compression wave speed, $\sigma = \rho'/\rho$ is the ratio of the solid density to the fluid density, a is the particle radius and $\beta = \sqrt{\omega/2\nu}$ is the reciprocal of the skin depth for viscous shear waves, with ω the angular frequency and ν the kinematic viscosity of the fluid.

2.3. Scattering

Many workers have investigated sound scattering from suspended spheres, and expressions may easily be found in the literature (e.g. Faran [13]) for the far-field scattering form function, f_∞. Such approaches generally treat the particle as a homogeneous sphere which may be: rigid and movable; rigid and immovable; or elastic. The elastic models in particular lead to complicated scattering form functions owing to resonant excitation. However, when dealing with naturally occurring sediment populations, the particles will be irregular in shape and size, and each particle will have differences in the detailed structure of the scattering form functions. Therefore, when considering the combined effect of a large number of such irregular particles, such details become smeared out, and it is appropriate to use a simpler form for the scattering form function. Such an approach was used by Johnson [14] in developing the so called high-pass model for backscattered intensity from a fluid sphere. Here, a simple polynomial in $x = ka$ is used to represent the scattering form function approximately by requiring that it fits the form of f_∞ exactly in the Rayleigh (small x) and geometric (large x) regimes. The exact amplitude scattering form function for a sphere varies as x^2 in the Rayleigh regime and becomes constant in the geometric regime, so a polynomial fit to this resembles the response curve of a high-pass filter, hence the nomenclature.

Sheng and Hay [15] constructed a high-pass model for the attenuation coefficient for scattering by a suspension of spheres, and their expression may be written

$$\alpha_s = (10 \log e^2) \frac{\epsilon K_\alpha x^4}{a \left(1 + \xi x^2 + \frac{4}{3} K_\alpha x^4\right)} \quad \text{dB m}^{-1} \tag{5}$$

where

$$K_\alpha = \frac{1}{6}\left(\gamma_\kappa^2 + \frac{\gamma_\rho^2}{3}\right) \tag{6}$$

and ξ is an adjustable constant ≥ 1. The ξ term allows the form of the polynomial to be adjusted to improve the fit to experimental data for intermediate x values. The terms γ_κ and γ_ρ are the compressibility and density contrasts given by

$$\gamma_\kappa = \frac{\kappa' - \kappa}{\kappa} \tag{7}$$

$$\gamma_\rho = \frac{3(\rho' - \rho)}{2\rho' + \rho} \tag{8}$$

where κ and κ' are the bulk compressibilities of the fluid and solid respectively.

3. Laboratory measurements

In order to validate the theoretical models and investigate the basic physics of the viscous absorption process a series of laboratory measurements of attenuation in suspensions is underway (Brown and Leighton [16, 17]). The method used exploits the reverberation behaviour of a volume of liquid to characterise the attenuation of the fluid. Differences in decay rate may be equated to variations in the absorptive properties of the fluid and the boundaries of the volume. The decay rates were obtained by applying the method of integrated impulse response (Schroeder [18]) to the measured sound field in the test volume after a broadband sound source was switched off.

Measurements were made on particulate-free water and then on water containing varying concentrations of glass beads. This type of particle has a high sphericity, enabling comparison with the theoretical models described in this paper. The particles have a narrow distribution of diameters, peaking at around 40 μm and this distribution has been taken into account in the calculations.

4. Sonar performance calculations

Simple sonar equation calculations have been used to investigate the effect of suspended particulate matter on sonar performance. These calculations, which are based on the methods used by Thomson and Foster [19], assume isovelocity conditions and uniform bathymetry, and multiple propagation paths have been neglected.

The active sonar equation for signal excess (SE) may be written

$$SE = EL - BG + PG \tag{9}$$

where EL is the target echo level, BG is the combined noise and reverberation background and PG is the processor gain.

The target echo level may be written

$$EL = SL + TS - 2TL + V_{pt} \tag{10}$$

where SL is the source level, TS is the target strength, TL is the one-way transmission-loss and V_{pt} is a vertical beam pattern correction factor to allow for target echoes which arrive off the main beam axis.

The transmission loss is assumed to be identical for both the forward and reflected pulse, and is approximated here by the sum of spherical spreading and volume attenuation

$$TL = 20\log(r) + \alpha r \tag{11}$$

where r is the one-way distance to the target and α is the total attenuation coefficient for seawater containing suspended particles, given by Equation 2.

The combined background level, BG is given by

$$BG = 10\log\left[10^{RL_s/10} + 10^{RL_b/10} + 10^{RL_v/10} + 10^{NL/10}\right] \tag{12}$$

where RL_s, RL_b, RL_v are the surface, bottom and reverberation levels and NL is the noise level. These terms have been calculated using the expressions used by Thomson and Foster [19]

The processor gain, PG, is given by

$$PG = 10\log(B\tau) \quad (13)$$

5. Results

Figure 1 shows the attenuation coefficient for 0.2 kg m^{-3} quartz particles suspended in seawater, calculated using Equation 2, with the viscous absorption and scattering terms given by Equations 3 and 5, and the clear water terms given by the Francois and Garrison expression. This figure clearly demonstrates how the viscous absorption peaks at a particular particle size for a given frequency. The attenuation also increases as the frequency and particle size become large (i.e. increasing ka) due to scattering.

Figure 2 shows the attenuation coefficient due to the spherical glass particles obtained from the experimental measurements. Experiments were carried out at different concentrations, and these have been normalised for concentration and compared with theoretical predictions using Equation 3 (note that scattering has not been included in these calculations as it does not represent a loss from this experimental system). It is clear from this figure that normalising the attenuation for concentration does not reduce the data to a single curve, the reasons for which are not yet understood. It may be that the measurements at low frequencies with the more dilute solutions were made near or below the Schroeder frequency, below which the sound field may not be considered to be fully diffuse. The Schroeder frequency reduces at higher concentrations as the reverberation time decreases. Given the small difference in attenuation between the dilute solutions and pure water, the departures from the predicted values are not altogether unreasonable. The measurements made at the higher concentrations agree reasonably well with the model predictions.

The method described in Section 4 has been used to calculate the Signal Excess (SE) for a typical high frequency, shallow water sonar operating at 120 kHz in 40 m of water. In this calculation a suspension of quartz particles of radius 1 μm with a concentration of 0.2 kg m^{-3} was used in the calculation of the absorption coefficient, together with the attenuation due to clear seawater using the Francois & Garrison expression for a temperature of 15°C, a salinity of 35 on the Practical Salinity Scale and a pressure corresponding that at half the water depth of 40 m. The target strength was taken to be -25 dB, the target depth was 40 m (i.e. at the seabed), the array depth was 20 m, and the detection threshold was 9 dB re. 1 μPa. The reverberation level (RL) shown in the figure is the total reverberation level due to seabed, surface and volume reverberation, using a wind speed of 15 knots and a bottom type of 2 (sand). Figure 3 shows the result of this calculation compared with the case without the suspended particles. If we define the detection range as being the range within which the signal excess exceeds the detection threshold, then the detection range shown in this figure is around 473 m with the suspended particles present, compared with about 660 m in the absence of the particles.

6. Conclusions

This paper describes a method for calculating the additional acoustic attenuation resulting from viscous absorption and scattering by the suspended mineral particles found in turbid coastal waters. The calculations of viscous absorption have been compared with experimental measurements and the agreement was found to be reasonable, although the attenuation data did not reduce to a single curve when normalised for concentration. Possible reasons for this are under investigation.

The attenuation due to suspended particles may be included in sonar performance prediction models by using a modified absorption coefficient, and calculations of this nature have been performed. The example calculation presented in this paper shows that a moderate concentration of quartz particles can have a significant effect on the detection range of high frequency sonars such as minehunting sonars.

In order to account for the effects of suspended particles operationally information regarding the suspension is required. In particular the particle radius, density and compressibility are required, together with the concentration and particle size distribution. Methods for obtaining these data using remote sensing, hydrodynamic modelling and *in-situ* measurements are under investigation.

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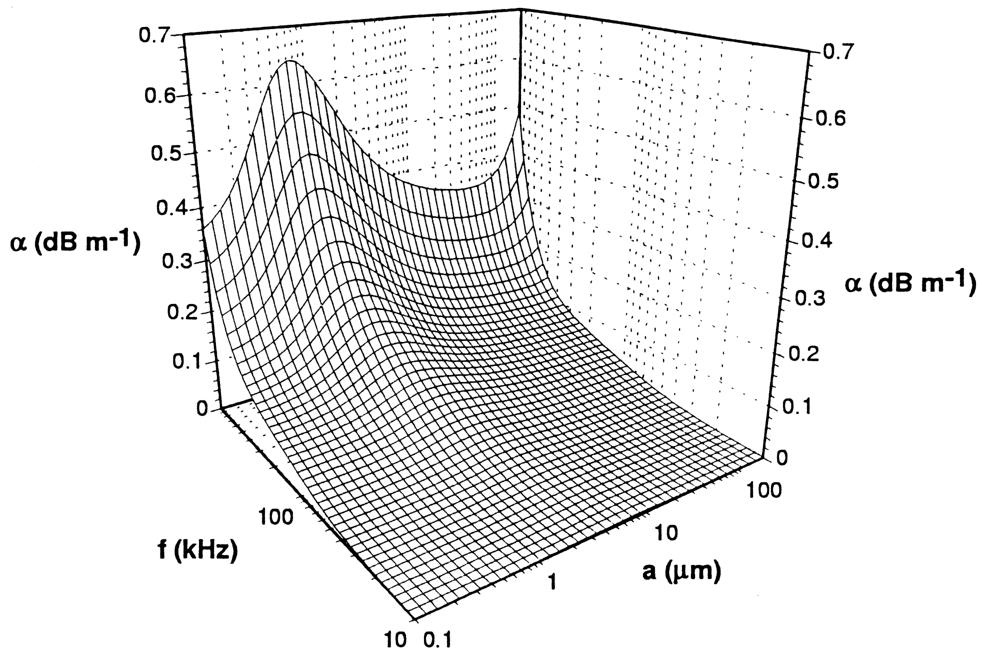

Figure 1: Attenuation coefficient for seawater containing 0.2 kg m^{-3} suspended quartz particles

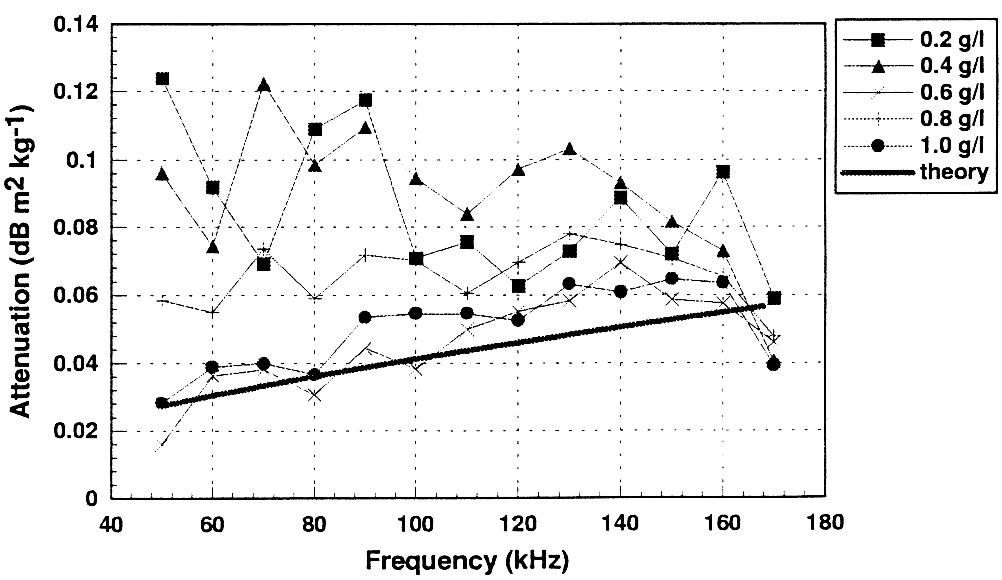

Figure 2: Normalised particulate attenuation measured at various concentrations, compared with model predictions

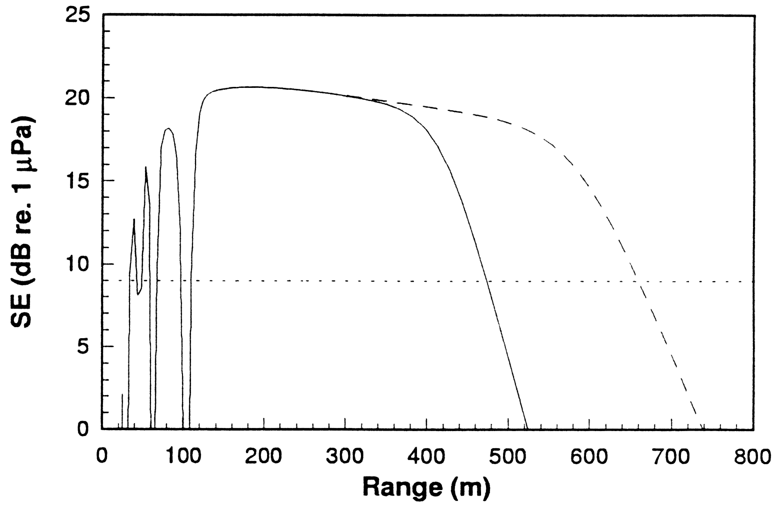

Figure 3: Signal excess with (solid) and without (dashed) 0.2 kg m^{-3} suspension of 1 μm quartz particles. The dotted line shows the detection threshold, DT