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► To cite this version:

Mohammad Alarab, Franck Augereau, Didier Laux, Lionel Lapierre. Estimation of particle size in turbid water using ultrasonic attenuation - Application for immersed cave exploration. Forum Acusticum, Dec 2020, Lyon, France. pp.2303-2306, 10.48465/fa.2020.0078 . hal-03240215

HAL Id: hal-03240215

<https://hal.science/hal-03240215>

Submitted on 29 May 2021

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Estimation of particle size in turbid water using ultrasonic attenuation _ Application for immersed cave exploration

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ABSTRACT

In this work, we have investigated the estimation of particles size, to prove the feasibility of a simplified acoustic system for continuous characterization of turbid water during underwater cave exploration with autonomous vehicles.

Because of the nature and concentration level of sediments in natural water networks, we have identified the most suitable models for suspended sediments. They were proposed by Urick [1] and Sheng & Hay [2] assuming that particles are movable, rigid and at low concentration. These models have the advantage to provide a simple analytical expression with a limited number of input parameters. In order to test a very simplified prediction tool, these models are used to calculate attenuation only for monodisperse particle size distributions

Experimentally, we used clay powder sifted to 40 μm , to create turbid water similar to cave water. This mixture characterised using laser diffraction spectroscopy shows a large and non-uniform particle distribution. From the measurement of the echo amplitude in reflexion mode, we deduce the attenuation coefficient in a frequency range from 1.5 MHz to 16 MHz. We used several transducers for different travel distances (3.5 cm to 7.5 cm) and different clay concentrations in volume (0.3 to 1.7 %). We obtained a linear dependence between attenuation coefficient and concentration for any tested frequency in total agreement with the selected model. Fitting experimental attenuation data with this model, the best agreement was obtained with a particle diameter of 70 μm . This value is in agreement with the standard Dv90 parameter provided by laser diffraction analysis. This is an encouraging result to validate our minimalist experimental setup and the selected model for a simplified implementable system for in situ characterization of turbid water.

1. INTRODUCTION

The characterization of turbid water consists in estimating the particles size or diameter ($2r$) and concentration (C). For many years, a lot of investigations have been made for this application, but they usually require complex laboratory systems. Our work aims to design and develop a miniaturized system for embedded applications. In the future, this device will be implemented on an underwater

vehicle dedicated to cave exploration, so it must be taken into account the limited resource in energy and computing. Furthermore, this system should be as compact as possible. The main goal is to get quantitative estimation of particles size and concentration from ultrasonic attenuation measurement in real time.

In this paper we focus this study on the estimation of particles size alone. So, at first, we present the chosen theories that link the attenuation coefficient to particles size.

Next, we present our experimental setup based on acoustic reflection method to measure the attenuation in turbid water. Then, these experimental results are adjusted with the selected theoretical model in order to estimate the particles size for comparison with particle size distribution obtained with a commercial laser diffraction spectrometer.

2. THEORY

The pressure of an ultrasonic wave after propagation through turbid water over distance x is given by,

$$p = p_0 e^{-\alpha x} \quad (1)$$

Where α is the attenuation coefficient of turbid water, and can be written as the sum of the attenuation of clear water (α_w) and of suspended sediments alone (α_{sed})

$$\alpha = \alpha_w + \alpha_{sed} \quad (2)$$

The loss through suspended sediments is due to two main mechanisms, viscous absorption and scattering effects. Each mechanism is represented by an attenuation coefficient (α_{visc} and α_{scat} respectively), and the total attenuation through suspended sediments can be written as the sum of these coefficients.

$$\alpha_{sed} = \alpha_{visc} + \alpha_{scat} \quad (3)$$

2.1 Viscous absorption

It occurs when wavelength (λ) is greater than particles circumference ($2\pi r$). In turbid water, the suspended sediments vibrate lags behind wave in the sound field. This lag is due to the viscosity of the water and the ratio of sediments density to water density. This loss increases with the fluid viscosity and with the surface of the liquid-solid interface.

Urick [1] calculated the attenuation coefficient due to the viscosity assuming the particles are spherical, rigid and movable. This loss expression may be written as:

$$\alpha_{Urick} = \alpha_{visc} = \frac{C}{2} \left[k(\sigma - 1)^2 \frac{s}{s^2 + (\sigma - \tau)^2} \right] \quad (4)$$

Where C is the concentration of suspended particles per volume unit, $C = n(4/3)\pi r^3$, n is the number of suspended particles per volume, k is the wave number, $k = 2\pi/\lambda$, λ is the wavelength of sound in water, $\sigma = (\rho_{sed}/\rho_w)$, ρ_{sed} and ρ_{water} are the density of sediments and water respectively, $s = \frac{9}{4\beta r} \left(1 + \frac{1}{\beta r} \right)$, $\tau = \frac{1}{2} + \frac{9}{4\beta r}$, $\beta = \sqrt{\frac{\omega}{2\nu}}$, ω is the angular frequency and ν is the kinematic viscosity of water.

2.2 Scattering effect

When ultrasonic wave passes through suspended sediments, its intensity will be redistributed in all directions depending on the ratio between the λ and $2\pi r$.

If $\lambda \gg 2\pi r$, the scattered intensity is concentrated in the backward direction, it is the back-scattering. In the range $\lambda \ll 2\pi r$, the scattered intensity is concentrated in the forward direction and the intensity distribution will be like a diffraction. $\lambda \approx 2\pi r$ is the transition zone between back-scattering and diffraction. Sheng & Hay [2] have proposed a global expression to calculate attenuation coefficient due to back-scattering and diffraction over the entire interval $2\pi r/\lambda$:

$$\alpha_{S\&H} = \alpha_{scat} = \alpha_{b-scat} + \alpha_{diff} = \frac{CK_\alpha X^4}{r(1 + \xi X^2 + \frac{2}{3}K_\alpha X^4)} \quad (5)$$

Where, $K_\alpha = \frac{1}{6} \left(\gamma_\epsilon^2 + \frac{\gamma_\rho^2}{3} \right)$, $\gamma_\epsilon = \frac{\epsilon_{sed} - \epsilon_w}{\epsilon_w}$, $\gamma_\rho = \frac{3(\rho_{sed} - \rho_w)}{2\rho_{sed} + \rho_w}$, $X = kr = \frac{2\pi}{\lambda} r$, ξ is a correcting factor ≥ 1 and $\epsilon_w, \epsilon_{sed}$ are the compressibility of water and sediments respectively.

Sheng & Hay model is based on the High-pass model of Johnson [3] who assumed the particles to be spherical, rigid and movable. They used experimental measurement existing in the literature like those of Flammer [4] to tune the model with experimental results and proposed their modified high-pass model as an improvement of the classic rigid movable case for low concentration mixtures.

In both equations (4 and 5), attenuation coefficient is linearly dependent on the sediment concentration, because they assume a low concentration of sediments (less than 20%) to consider that there is not any interaction between particles.

3. MATERIAL AND METHODS

3.1 Experimental Setup

To measure the attenuation coefficient in turbid water and compare with the theory, we used acoustic reflection method for the simplicity of this configuration.

An ultrasonic transducer was placed in front of a polyoxymethylene reflector (POM). Transducer and reflector were immersed in turbid water contained into a conical vessel to improve the suspension homogeneity. To suspend the sediments during measurements, we used a magnetic propeller with a magnetic agitator placed at the bottom of this vessel. The emitter-reflector distance could be varied if necessary.

We used 3 different transducers with different resonance frequencies, 2.25 MHz, 5.5 MHz and 15 MHz. These transducers have been used to measure the attenuation between 1.5 MHz and 16 MHz with a step of 0.5 MHz. We used a 10 volt peak to peak single frequency tone burst with 20 cycles to excite the sensor. Reflected wave has been detected, then filtered (low pass at 20 MHz) and amplified (20 dB), then averaged 256 times.

The measurement protocol consisted in measuring in the first step, the amplitude in the time domain of the reflected echo in pure water over our investigation frequency interval ($A_w(f_i)$). This measurement was the reference one. In the second step, we added a volume of particle in the water and we measured the new echo amplitude for the different frequencies and concentrations ($A_{w+sed}(f_i, C_i)$). We maintained exactly the same experimental configuration for the reference measurement and the measurement with particles. Dividing ($A_{w+sed}(f_i, C_i)$) by the pure water reference amplitude ($A_w(f_i)$) should withdraw the instrument system response and all the systematic source errors (sensor to reflector misalignment, sensor field diffraction, interface reflection coefficient, etc) to get the attenuation due to suspended particles alone.

3.2 Sediments characteristics

To create turbid water, we used commercial clay powder sifted to 40 μm . We used laser diffraction analyses to get the particles size distribution. The Figure 1 and Table 1 show the results of this standardized characterization.

Distribution in volume	Size in μm
Dv10 (10 th percentile diameter)	2.8
Dv50 (50 th percentile diameter)	16.7
Dv90 (90 th percentile diameter)	62.2
D [4;3]	25.7

Table 1. Particles size distribution of clay powder.

Where Dv10, Dv50 and Dv90 respectively indicate the size point below which 10%, 50% and 90% of the product in volume is contained. Dv50 is also called the median size and D [4;3] the mean size.

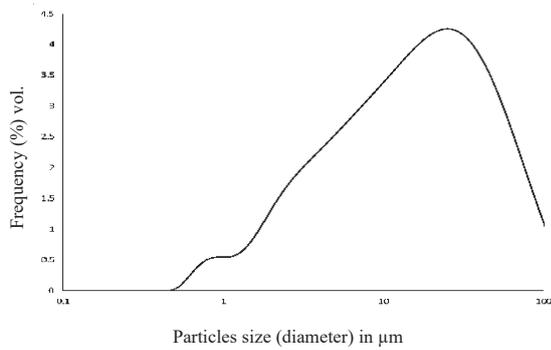


Figure 1. Particles size distribution of clay powder

These results show that particles in this clay powder have a large distribution close to a log-normal function. Thus, 80% of particles have a size between 3 μm and 62 μm .

4. RESULTS

First, we plot on the figure 2 our experimental attenuation coefficient versus concentration of sediments for different investigation frequencies. We find a linear dependence between α and C in accordance with the theory. This dependence indirectly also proves the good homogeneity of the sediment mixture during agitation and that the concentration range is suitable for the selected model. Moreover, these results attest the reliability of the experimental setup.

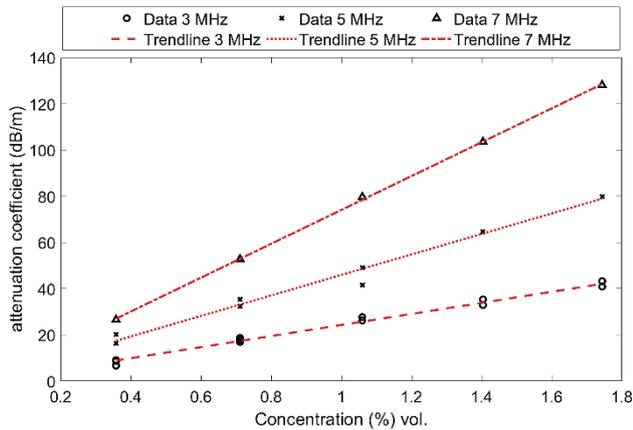


Figure 2. Attenuation coefficient due to clay powder.

Because of the linear dependence between α and C , we can normalize attenuation coefficient to concentration. This is a way to represent all experimental results on the same graph. Thanks to this normalization, we get a monotonous curve over a large frequency range which is a more favorable situation to succeed in data fitting. Indeed, attenuation can be difficult to measure for low concentration when echo amplitude is too slightly modified by the sediment presence or, at the opposite, when attenuation is too high compared to the signal to noise ratio.

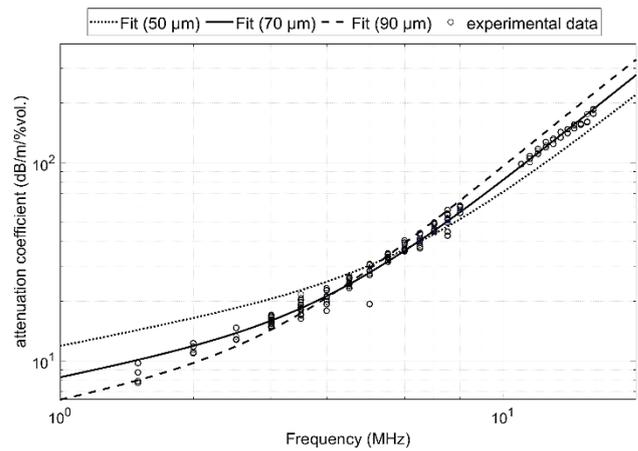


Figure 3. Attenuation coefficient due to clay powder

Figure 3 shows our experimental results (more than 210 points) made with 3 different sensors, at different distance between sensor-reflector (from 3.5 cm to 7.5 cm) and for different concentrations of sediments (from 0.3% to 1.7% in volume).

The results prove a very good reproducibility of the measurement with a standard deviation from 5% to 10% with the 2.25 MHz sensor, from 3.5% to 10% with the 5.5 MHz sensor, and from 0.7% to 3.5% with the 15 MHz sensor.

To fit our data, the input parameters for theoretical models are:

ρ_w	1000 kg/m^3
ρ_{sed}	1850 kg/m^3
c_w	1500 m/s
ν	$1.3 \cdot 10^{-6} \text{ m}^2/\text{s}$
γ_ϵ	1 assuming particles and water are not compressible
ξ	3

Table 2. Input parameters for theoretical models.

Three adjustment curves are superposed on this graph for three values of particles size: 50, 70 and 90 μm . The best adjustment corresponds to a particle size of 70 μm .

The particle size estimated from ultrasonic attenuation spectrometry is close to the Dv_{90} parameter found with laser diffraction analyses.

We assume, for these frequencies and particles size range that ultrasonic waves are more sensitive to the biggest particles. Therefore, we tested other powders (up to 200 μm of particle diameter) to prove this assumption, and we always found an acoustically estimated particle size close to the Dv_{90} parameter. These results will be published in a future work.

5. CONCLUSION

In this work, we were interested in the estimation of particles size in turbid water using a robust acoustic reflection method easy to implement. We used clay powder to create turbid water with low concentration of sediments, and we fitted our results with the chosen

theoretical models to deduce particles size. We found an estimation of size in agreement with the value of the $Dv90$ parameter issued from laser diffraction analyses.

These results prove the possibility to estimate particles size using our acoustic reflection method and set-up. The next step will be the simultaneous estimation of the concentration of sediments in addition to particles size in an attempt to prove the feasibility of a simplified acoustic system for continuous characterization of turbid water, embedded on an autonomous underwater vehicle.

6. ACKNOWLEDGMENT

This work has received the financial support of the LabEx NUMEV foundation and the research Institute IES - UMR 5214 CNRS from Montpellier University. We are also grateful to L. Dahdouh from the CIRAD-UMR Qualisud organization who performed the DLS analysis.

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