

Acoustic attenuation of cohesive sediments (mud) at high ultrasound frequencies

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**Underwater Acoustics: Sediment Imaging
and Mapping****Acoustic attenuation of cohesive sediments (mud) at
high ultrasound frequencies****Bart Brouwers***SPFO, Flanders Hydraulics Research, Antwerp, 2140, BELGIUM; bart.brouwers@mow.vlaanderen.be***Jeroen van Beeck***Environmental and Applied Fluid Dynamics Department, Von Karman Institute For Fluid Dynamics, Sint-Genesius-Rode, Vlaams-brabant, 1640, BELGIUM; jeroen.vanbeeck@vki.ac.be***Evert Lataire***Department of Civil Engineering, Maritime Technology Division, Ghent University: Universiteit Gent, Ghent, Oost-vlaanderen, 9052, BELGIUM; evert.lataire@ugent.be*

The acoustic attenuation of cohesive sediment (mud) at high frequencies ranging from 0.5 MHz to 5.0 MHz is determined. Conventional laboratory experiments based on the pulse-echo technique were performed using a single element immersible ultrasound transducer. The results showed however that due to the time-changing properties of mud a different approach to process the data is required. Additional experiments to determine the acoustic attenuation using multiple alternative ultrasonic devices were conducted. Using the results of the conventional experiments as a benchmark the reliability of these experiments is considered acceptable. This manuscript was originally submitted to the ICUA 2022 conference.

1. INTRODUCTION

As the clearance between the keel of a ship and the bottom of a navigation channel greatly influences the controllability of the ship, the passage of large ships through shallow and confined navigation channels results in specific recommendations for safe navigation. This subject is therefore a specialized discipline in the nautical community. The presence of a fluid mud layer on the bottom of such waters makes the comprehension of the ship's behavior even more challenging. Fluid mud is a saturated mixture of water and sediments with a high clay and organic fraction. The density of highly consolidated mud can be as high as $1300 \text{ kg} \cdot \text{m}^{-3}$. The particles form a continuous network, a soil skeleton, and therefore a yield stress needs to be overcome before the material will flow (i.e. non-Newtonian fluid). In addition mud shows thixotropic behavior, meaning its viscosity decreases with stress over time or vice versa when left at rest.¹ The interactions between ship, water and mud in such situations therefore have been and still are the subject of many nautical research projects.² To facilitate such research, both CFD models and physical laboratory experiments are used. In these physical experiments the flows induced by a passing ship are of great interest. Although alternative approximations using artificial mud have been used extensively,³⁻⁵ the ability to perform such tests with real mud is still the preferred option. Nonetheless there are no techniques available today to visualize flows and measure flow velocities in mud. In a yet unpublished manuscript⁶ ultrasound speckle tracking is proposed to resolve this deficiency. A first test using a standard medical ultrasound scanner equipped with a linear array set at 7 MHz proved the ability of this technique. Due to the attenuation of the ultrasound radiation by the mud, the depth to which flows were recorded was however limited to only a few centimeters. Decreasing the frequency will allow for greater penetration depths, but at the expense of a degradation in speckle image quality. A minimal speckle quality is required to allow for the application of image processing algorithms. Further development of this technique thus comes down to a trade-off between penetration depth and speckle image quality, which requires a better knowledge of the acoustic attenuation of mud.

In general, ultrasound imaging is performed in the MHz frequency range. When the depth of the object to be visualized predominates the resolution at which the object is depicted, e.g. fish spotting, frequencies of 0.7 MHz to 2.0 MHz will suffice.⁷ In case the images are produced for diagnostic requiring high resolution, higher frequencies are required at the cost of penetration depth. For medical imaging this can go up to 15 MHz.⁸ When speckle images are the objective there is no need to clearly visualize a boundary or interface. Speckle patterns are conceived by the interferences of multiple backscattered signals which add up or cancel each other out. Hence resolution is replaced in this trade-off by the amount of backscattering, which is determined by the ratio of wavelength of the ultrasound radiation to the size of the scatterers. The particle size distribution of cohesive sediment from the Port of Zeebrugge (Belgium) indicate an optimal ultrasound frequency range between 1 MHz and 10 MHz to generate speckle patterns.⁶ For this research a frequency range of interest is therefore set from 1 MHz to 7 MHz. To the authors' knowledge, values for acoustic attenuation of mud in this frequency range are not documented in existing literature,⁹ which calls for the need of experiments.

The most straightforward method to measure the attenuation of a medium (solid or liquid) is with the so-called through-transmission technique.^{10,11} This technique requires two transducers placed opposite to each other. One transducer transmits the ultrasound waves while the other receives (Fig. 1A). In case the properties of the liquid are of interest, the two transducers are immersed in the liquid. The acoustic attenuation can be deduced by comparing the amplitude received after propagation of the ultrasound wave through the liquid with a reference signal. The latter is preferably obtained from calibration in water as water has low acoustic attenuation values which in fact can be neglected.¹² The through-transmission demands the two transducers to have at least equal center frequencies.

A technique requiring only a single transducer is the pulse-echo technique.^{13,14} Here the transducer works as transmitter and receiver (Fig. 1B). Again the transducer is immersed in the liquid of interest,

but now an acoustic reflector is placed opposite to the transducer and perpendicular to the wave direction. The emitted ultrasound signal propagates through the liquid, reflects on the acoustic reflector propagates back to the transducer. Relative measurement (See Section 2.2.1) of the reflection signal amplitude over multiple acquisitions with varying distance between transducer and reflector allows to determine the acoustic attenuation in the liquid.

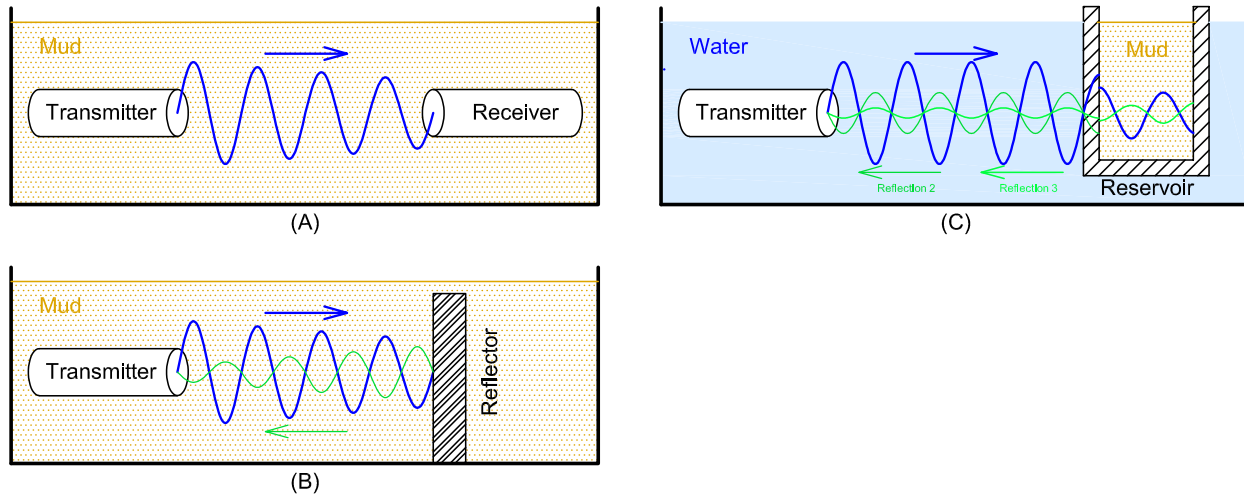


Figure 1: Possible experimental setups using immersible transducers to determine the attenuation of mud. (A) Setup for the through-transmission technique, (B) Setup for the pulse-echo technique, (C) setup for the multiple-echo technique.

Immersion of the ultrasound transducers for long periods or in media other than clear water can however cause contamination of the sensor surface, influencing the recordings and damaging the transducers.¹⁵ In case of mud this could be caused by the corrosive nature of the seawater present in mud. In such cases an alternative multiple-echo technique can be an option.¹⁶ In this method a secondary reservoir containing mud is immersed in water together with the transducer (Fig. 1C). The attenuation is obtained from comparison between the reflection signals of the two reservoir/mud interfaces. This method suffers however from great energy losses. Before reaching the liquid of interest, energy is already lost by reflection on the water/reservoir interface and propagation through the reservoir material. Such losses can be compensated by amplifying the signals, however at the cost of accuracy.

Since a pair of transducers with equal centre frequency were not available for this research, the through-transmission technique (Fig. 1A) could not be considered. While the relativity (See Section 2.2.1) of the pulse-echo measurement technique (Fig. 1B) allows to simply protect the transducer from contamination by inserting it in a thin sheath-shaped rubber, the pulse-echo technique was preferred for these experiments. Additional experiments determining the acoustic attenuation of mud were performed using various acoustic devices. The results are compared with those using the submersible transducer to evaluate the reliability of alternative ultrasound techniques for the purpose of similar future research. The used acoustic devices were all developed for other applications like on-site marine measurements (Admodus USP pro and AQUAscot 1000R) and medical echography (DiPhAS beamformer platform and FI Toolbox). Nonetheless their output can be used to deduce the acoustic attenuation of mud. The different methods are presented in this paper and the results compared with the results from the pulse-echo experiments. All experiments were conducted with the same unique mud samples from the Port of Zeebrugge with differentiating densities of $1115 \text{ kg} \cdot \text{m}^{-3}$, $1450 \text{ kg} \cdot \text{m}^{-3}$ and $1175 \text{ kg} \cdot \text{m}^{-3}$.

In addition to the development of ultrasound velocimetry techniques, knowledge of the acoustic attenuation of mud is also of interest for the study of the rheological properties of mud. Such properties are of

interest for the study of ship, water and mud interactions and multiple other topics.^{17,18} Rheological properties can be determined using a rheometer.¹⁹ Due to practical reasons this is performed in a laboratory. Obtaining the properties from on-site mud layers therefore requires on site sampling and transport towards the lab, which is a laborious operation. Furthermore for continuous monitoring, this procedure should be repeated frequently as mud layer properties change over time²⁰ and are continuously influenced by tidal currents, ship passing and dredging.¹ The ability to perform fast on-site measurement of the rheological properties of mud would therefore be of great interest. In the drilling industry recent research has shown that ultrasonic measurements in non-Newtonian fluids like drilling mud exhibit a non-linear relationship between the acoustic attenuation and rheological properties of the fluids.²¹ The results presented in this paper could help to assess whether or not this relation also holds true for cohesive sediments.

The main objective of this research is to determine the acoustic attenuation of mud at high ultrasound frequencies. A conventional method to determine the acoustic attenuation of common fluids is used. Mud can however not just be considered as a common fluid as its properties change with time, when at rest. A correction of the attenuation values by alternative processing of the experimental output is therefore suggested to cope with such properties (see Section 2). These corrected values are further used as reference to evaluate the reliability of alternative experiments, to determine the acoustic attenuation of mud, using various ultrasound techniques. These experiments are discussed in Section 3.

2. REFERENCE EXPERIMENT USING AN IMMERSIBLE TRANSDUCER

A. SETUP AND MEASUREMENTS

The experimental setup used to assess the acoustic attenuation of mud is based on the pulse-echo technique (Fig. 1B). In practice the setup was however slightly different, as depicted in Fig. 2A. To facilitate the changing distance between transducer and reflector a high precision XYZ gantry stage was used to hold the transducer upright with the emission side facing down in the top layer of the mud. The mud sample was contained in a plastic bucket, positioned underneath the gantry stage. The used transducer is an immersible broadband (fraction bandwidth 50 %) transducer type H5K from General Electric.²² In mud with density $1145 \text{ kg} \cdot \text{m}^{-3}$ the centre frequency produced by the transducer is around 2.75 MHz. Due to the high attenuation values of mud the ultrasound waves were amplified (gain) using a pre-amp. A gain of 40 dB was applied for all mud samples. Stainless steel was chosen as the material for the acoustic reflector. With a speed of sound in stainless steel¹⁰ of $5800 \text{ m} \cdot \text{s}^{-1}$ and a density of $7850 \text{ kg} \cdot \text{m}^{-3}$ the acoustic impedance of steel can be calculated using Eq. 1. The same can be done for each mud sample with known density and a speed of sound⁶ of $1465 \text{ m} \cdot \text{s}^{-1}$. With the impedance of both media the reflection coefficient of their interface can be determined using Eq. 2.

$$Z_i = c_i \cdot \rho_i \quad (1)$$

Z is the acoustic impedance [$\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$], c is the speed of sound through the medium [$\text{m} \cdot \text{s}^{-1}$], ρ is the density of the medium [$\text{kg} \cdot \text{m}^{-3}$] and i the index referring to the medium.

$$r_{ij} = \frac{Z_j - Z_i}{Z_j + Z_i} \quad (2)$$

r is the reflection coefficient [-], Z is the acoustic impedance [$\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$] and i and j are the indices referring to the encountered materials or media.

The resulting reflection coefficient of the mud/reflector interface is around 0.93 meaning 93 % of the incoming ultrasound radiation is reflected back towards the transducer. A plate of 10 cm by 10 cm and 1 cm thickness was placed at the bottom of the mud bucket. Using the XY positioning system of the gantry,

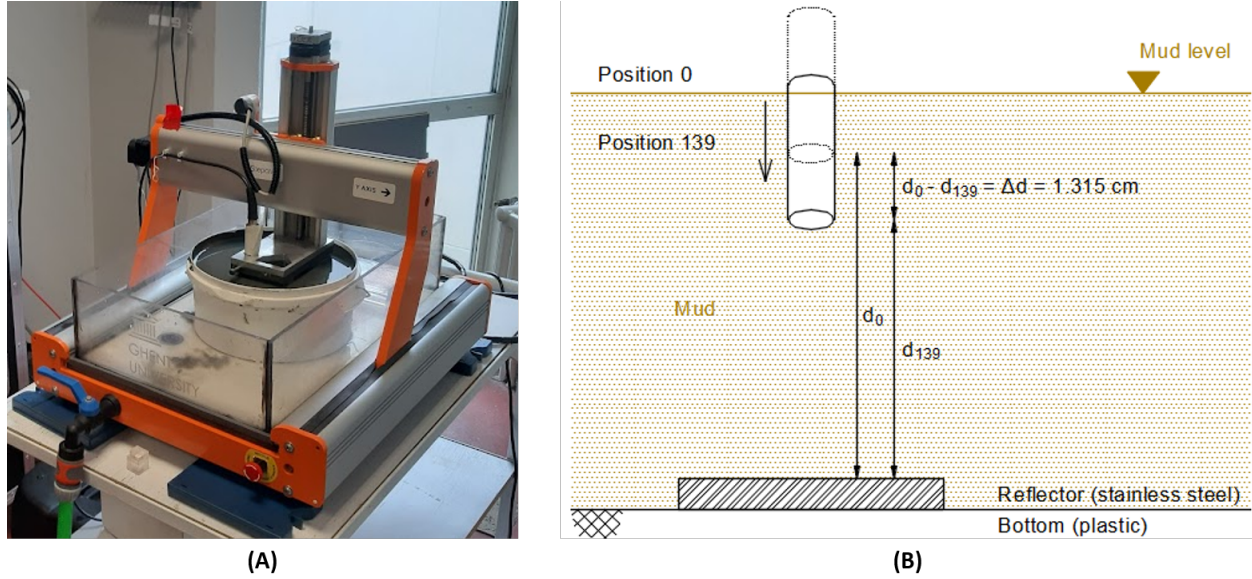


Figure 2: (A) Laboratory setup of the experiments using an immersible transducer. The transducer is held vertically with its immersive side in the mud, while protected by a sheath-shaped rubber. The gantry stage is used for vertical displacement of the transducer. (B) Sketch of the experimental setup shown in Fig. 2A, illustrating the effects of the transducers' displacement.

the transducer was positioned more or less above the center of the reflector. Adjustment of the distance between transducer and reflector was performed by moving the transducer towards the reflector. For each mud sample this was done in 140 steps, covering a total displacement of 1.315 cm (Fig. 2B). At each step a scan was conducted, recording the amplitude of the reflected signal. The amplitude of the reflected signal can be expressed as:

$$A_R = A_0 \cdot P_m \cdot r_{ms} \cdot P_m = A_0 \cdot r_{ms} \cdot P_m^2 \quad (3)$$

Where A_R is the amplitude of the reflected signal [V], A_0 is the amplitude of the emitted signal [V], r_{ms} is the reflection coefficient of the mud/stainless steel interface [-] and P_m the propagation loss due to attenuation by the mud [-]. Fig. 1B and Eq. 3 show that loss in amplitude is caused first by attenuation when sound waves propagate through the mud towards the reflector P_m . Secondly, energy is lost at the mud/reflector interface. The reflection coefficient r_{ms} shows us that 93 % of the amplitude is reflected back. The remaining 7 % propagates further through the stainless steel and is no longer used. Finally, while propagating back towards the transducer, the reflected signal is attenuated again over the same path as the initial incoming ultrasound wave (P_m). The propagation loss P_m can be expressed with the Beer Lambert Law Eq. 4,²³

$$P_m = e^{(-\alpha_m \cdot d_m)} \quad (4)$$

Where P_m the propagation loss due to attenuation by the mud [-], α_m is the frequency dependent acoustic attenuation of mud [$\text{Np} \cdot \text{m}^{-1}$] and d_m the propagation path of the ultrasound wave through mud [m].

B. PROCESSING OF MEASUREMENTS

The recorded reflection signals are transformed into the frequency domain by Fast Fourier Transformation. This allows to select the reflection signal amplitudes and calculate the acoustic attenuation for each frequency step. For these experiments the frequency band was cut in steps of 12.5 kHz.

When at rest, the density profile of a mud sample changes over time due to sedimentation.²⁰ Therefore it can be questioned if a method to determine the acoustic attenuation of a conventional fluid is best suited for mud. Two different ways to cope with this challenge are described and compared in this section. Prior to the experiments the mud was mixed to re-homogenize and negate the undesirable effect of sedimentation.²⁴ The first processing method assumes a homogeneous mud sample and is based on relative measurements, making knowledge of the value of some parameters unnecessary. The second approach assumes a non-uniform density profile of the mud sample and processes each scan separately. This method however requires knowledge of the values of variables which were obsolete for the conventional method. Therefore additional measurements are required at the risk of deteriorating reliability due to error propagation.

i. Conventional method

The reflection signal amplitude of the first position of the transducer is used as a reference ($A_{R,0}$ at $d_{m,0}$). From the ratios with the reflection signal amplitudes recorded at other positions of the transducer ($A_{R,n}$ at $d_{m,n}$) the attenuation of mud can be deduced. Combining Eq. 3 and Eq. 4 results in:

$$\alpha_m = \frac{1}{2 \cdot (d_{m,n} - d_{m,0})} \cdot \ln \frac{A_{R,0}}{A_{R,n}} \quad (5)$$

Where α_m is the frequency dependent acoustic attenuation of the liquid [$\text{Np} \cdot \text{m}^{-1}$], d_m the propagation path of the ultrasound wave [m], A_R is the amplitude of the reflected signal [V], index 0 refers to the reference scan and index n to a scan at a different position of the transducer (0-139). In practice, the logarithm of the ratio of the reflection signal amplitudes recorded at each position of the transducer with the reference signal amplitude is plotted in function of the transducers' displacement ($d_{m,n} - d_{m,0}$). The slope of the linear trendline fitting these ratios is a measure of the attenuation. Mathematically this procedure corresponds to Eq. 5. Following this procedure for each frequency step allows to determine the acoustic attenuation in function of frequency over the entire frequency band of the transducer. This was repeated for each mud sample with different density. The results are presented in Fig. 3A, indicating a linear relation between attenuation and frequency, common for most engineering materials.²⁵

ii. Alternative method

The presented conventional method may be improper because it determines the attenuation over a limited part of the mud sample only. In the described experiments a layer of 1.315 cm (Fig. 2B). This is not an issue for homogeneous fluids. Mud can however not be considered as a homogeneous fluid due to sedimentation when at rest. With mixing this can be minimized. However, as soon as the mud is at rest again, sedimentation starts, making mud in theory instantly inhomogeneous.²⁰ It is therefore recommended to conduct the ultrasonic scanning immediately after the conditioning of the mud. Practically this is however not always possible, casting doubt on whether a limited top layer is representative of the complete mud sample. To verify this possible inaccuracy, an alternative method to process the recorded reflection signals was performed. A major advantage of the first method is its relative approach, eliminating the need for knowledge of the originally emitted amplitude A_0 and reflection coefficient r_{ms} . Nonetheless with additional experiments in water the values for A_0 can be determined for each frequency. While the speed of sound in mud can be deduced from the scans performed in mud, enabling to verify the estimated value for r_{ms} . Subsequently the propagation loss P_m can be calculated for each scan using Eq. 3 and attenuation α_m using Eq. 4. Averaging the outcome over the 140 scans for each frequency step results in the curves presented in Fig. 3B. The results from this method show an even more linear relationship between attenuation and frequency, at least for frequencies above 1 MHz.

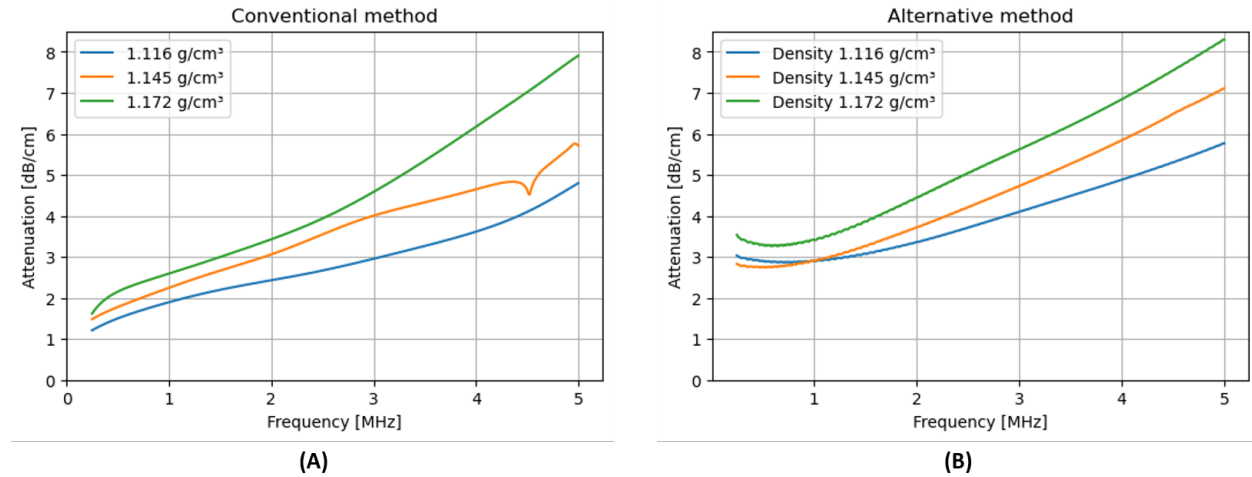


Figure 3: (A) Results for acoustic attenuation in function of ultrasound frequency per mud density determined using the conventional method for fluids, considering mud as a homogeneous fluid (Section 2.2.1). (B) Results for acoustic attenuation in function of ultrasound frequency per mud density determined using an alternative method for fluids considering mud as a inhomogeneous fluid (Section 2.2.2).

iii. Comparison of both methods

In case of perfectly homogeneous mud, the results of both methods should match. This is however not the case as shown in Fig. 3A and Fig. 3B. While the precision of the conventional method can be questioned due to the inhomogeneous mud, the alternative method suffers from error propagation due to usage of multiple measured values. A reliability analysis was therefore performed for both methods. For the conventional method R^2 values were calculated, indicating how well the trendline fits the recorded relative amplitudes (Fig. 4A). Reliability of the alternative method is evaluated with the standard deviation values of the averaged results (Fig. 4B). Both show similar trends with good reliability within and rapidly increasing inaccuracy outside the frequency band of 1.5 MHz to 3.5 MHz. This frequency band corresponds to the fractional bandwidth of 50 % and center frequency of 2.75 MHz as mentioned in Section 2.1.

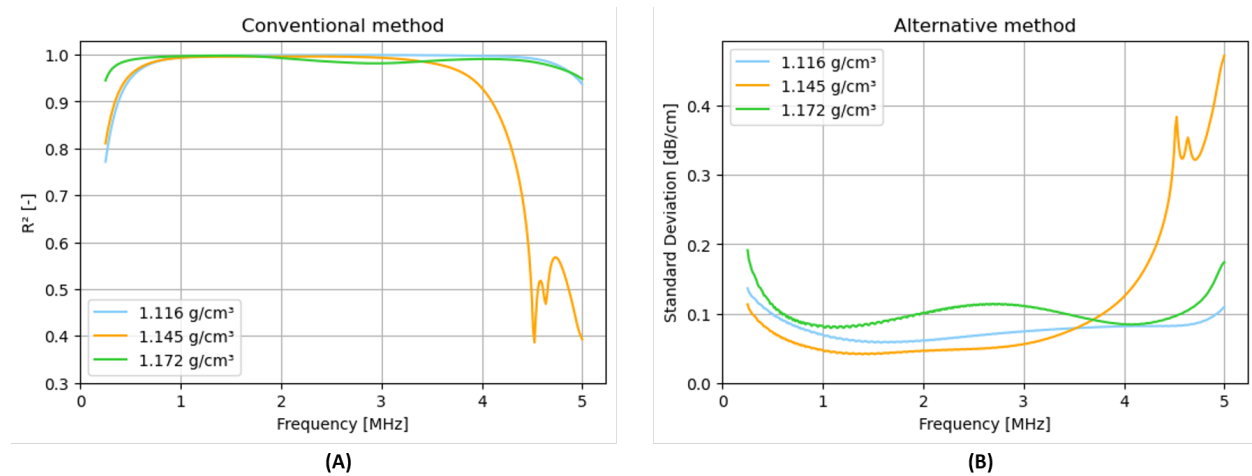


Figure 4: (A) R^2 values plotted in function of frequency representing the reliability of the outcome using the conventional processing method. (B) Values of standard deviation plotted in function of frequency representing the reliability of the outcome using the alternative processing method.

C. ACOUSTIC ATTENUATION VALUES OF MUD

To conclude, the average of the two methods is considered to be the best assessment for the acoustic attenuation in function of ultrasound frequency. The highest reliability applies to frequencies within the fractional frequency band Fig. 5. In addition to the relation between acoustic attenuation and frequency, the results show a linear relation between attenuation and density as well. An empirical equation Eq. 6 can therefore be determined expressing the relation between the three properties.

$$\alpha_m = (7.035f + 8.831) \cdot (\rho_m - 1) \quad (6)$$

where α_m is the acoustic attenuation [$\text{dB} \cdot \text{cm}^{-1}$], f the ultrasound frequency [MHz] and ρ_m the mud density [$\text{g} \cdot \text{cm}^{-3}$]. This equation is based only on the results within the fractional bandwidth and provides a good agreement with the averaged curves as depicted in Fig. 5.

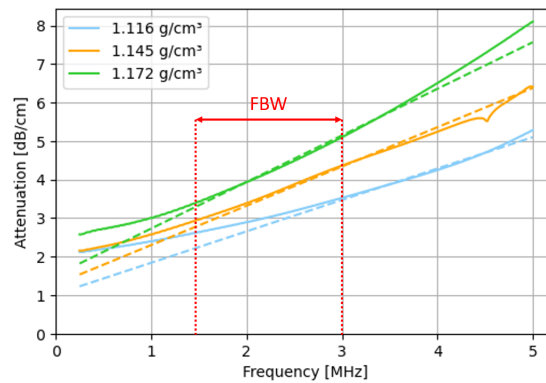


Figure 5: Calculated values of acoustic attenuation using Eq. 6 (dashed curves) compared to measured values of acoustic attenuation (solid curves). The fractional bandwidth (FBW) of the transducer is indicated in red.

3. ALTERNATIVE EXPERIMENTS USING VARIOUS ULTRASOUND EQUIPMENT

Immersible transducers and associated equipment are not always directly available. Nonetheless, a quick assessment of the acoustic attenuation of a medium can be of great value for a first feasibility study of an experimental setup or new technique. Due to the extensive scope of ultrasound, it is likely that some other type of acoustic equipment is more readily available. Although the application of such equipment might be very different, it can still be of use to assess the acoustic attenuation. This was put to the test by performing additional experiments using various acoustic equipment designed for a variety of applications and consequently using different ultrasonic principles. Unless mentioned otherwise all these experiments were conducted in the same mud samples as used with the immersible transducer and preconditioned by mixing. The results are benchmarked against the results presented in Section 2.

A. BACKSCATTERING BASED TECHNIQUES

Insonification of mud within the sound frequency band of 1 MHz to 7 MHz results in Rayleigh scattering of the ultrasound waves.⁶ Similar to the pulse-echo technique (Fig. 1B) a single transducer can therefore transmit and record the backscattered signals. Based on these recordings the acoustic attenuation can be deduced by the fading of the backscattered intensity with increasing penetration depth. The recording of backscattered signals requires highly sensitive transducers. Ultrasound transducers can be designed in different ways to create specific characteristics such as sensitivity. Customizable features are the piezoelectric

element and backing, which both can vary in size and thickness.²⁶ High ultrasound frequencies require thin piezoelectric elements while width and focus depth of the ultrasound beam are proportional to the element size.²⁷ The damping capacity of the backing determines the pulse length, which in turn defines the bandwidth of the transducer. High damping results in short pulse lengths and consequently in wide bandwidths. Low damping produces longer pulse lengths and narrow bandwidths. Narrow bandwidth transducers are considered to be more sensitive compared to broadband transducers which in turn result in a higher axial resolution due to the shorter pulse length.²⁸

i. AQUAscat 1000R

The AQUAscat 1000R is a device developed by the Aquatec Group Ltd for on site monitoring of sediment concentration, turbidity and particle size.²⁹ It uses multiple ultrasound transducers which act as transmitter and receiver. The device used for this research is equipped with 4 transducers of 0.5 MHz, 1 MHz, 2 MHz and 4 MHz. Because of its intended use the transducers are narrowband transducers,³⁰ making them highly sensitive at the cost of poor axial resolution as elaborated in Section 3.1. To determine the acoustic attenuation of mud, all transducers were submerged in the different mud samples. As attenuation is based on the recordings of the backscattered signals, there should only be sufficient mud in front of the transducers. This to allow for the recording of the decay of the backscattering intensity with penetration depth. A mud layer of 5 cm to 10 cm is considered to be sufficient for the applied ultrasound frequencies. The recordings for each transducer are presented in Fig. 6A. They show a clear fading of the backscattered intensity with increasing depth. The slope of the linear trendlines fitting the measurements, are a measure for the attenuation of the ultrasound by mud. In total 150 scans were conducted with each transducer in each mud sample, resulting in 150 values for acoustic attenuation per frequency. Final results are obtained by averaging these series of 150 values. The resulting values for acoustic attenuation per mud density are presented in Fig. 6B.

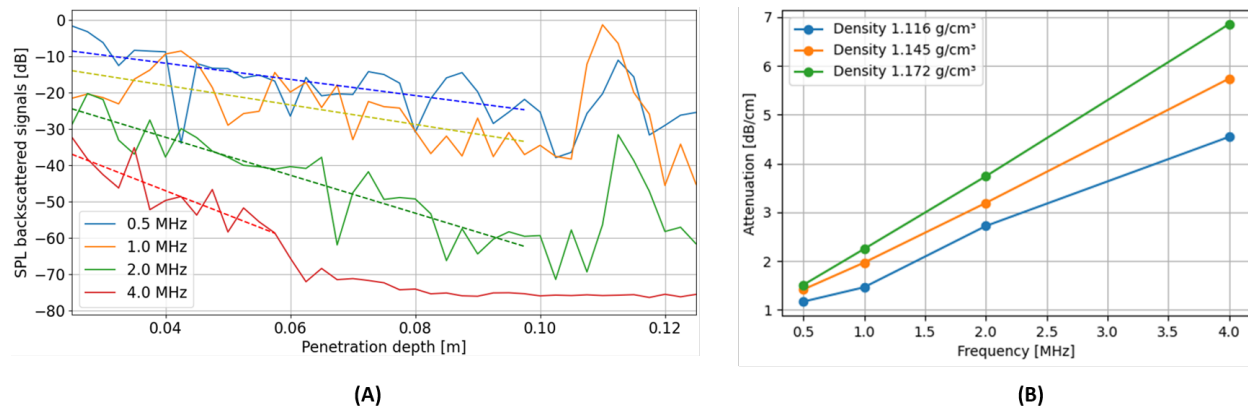


Figure 6: Results of experiments using the Aquascat 1000R. (A) Recordings of each transducer deployed in mud with density $1116 \text{ kg} \cdot \text{m}^{-3}$. The Sound Pressure Levels (SPL) of the received backscattered signals are plotted in function of penetration depth. The dashed trendlines fit the decreasing trend of backscattered SPL. Their slope represents the attenuation. The peak at approximately 0.115 m is the reflection on the plastic of the bucket. (B) Resulting values for acoustic attenuation.

ii. Medical ultrasound scanners

Probably the most commonly known application of high frequency ultrasound is that of medical imaging. Two medical acoustic scanners were used to create ultrasound images of mud. The scanners are

specifically developed for research purposes, enabling them to cover a broad frequency range. One scanner is the DiPhAS beamformer platform,³¹ the other the FI Toolbox (Diagnostic Sonar Ltd., Livingston, UK). A flexible linear array, a phased array and a conventional linear array with corresponding centre frequencies of 2.5 MHz, 3.5 MHz and 7.5 MHz were used to cover a total frequency band from 1.75 MHz to 6.67 MHz, in steps of approximately 0.5 MHz. In B-mode, or brightness-mode, the amplitude of the received signals is converted into pixel brightness. High amplitudes result in bright pixels and vice versa. Due to the large amount of scatterers many backscattered waves are created, causing them to interfere with each other by adding up or cancelling each other out. In the end this interference results in pictures with a mix of bright and dark pixels, so-called “speckle pattern” images,⁶ as presented in Fig. 7A. With image processing techniques, pixel brightness profiles can be converted to Sound Pressure Level (SPL) profiles and plotted in function of penetration depth per pixel column. The decay of the SPL with increasing penetration depth can then be expressed with a linear trendline fitting the SPL plots, Fig. 7B. The slope of the trendline is a measure of the acoustic attenuation of mud, similar as with the AQUAScat 1000R, Section 3.1.1.

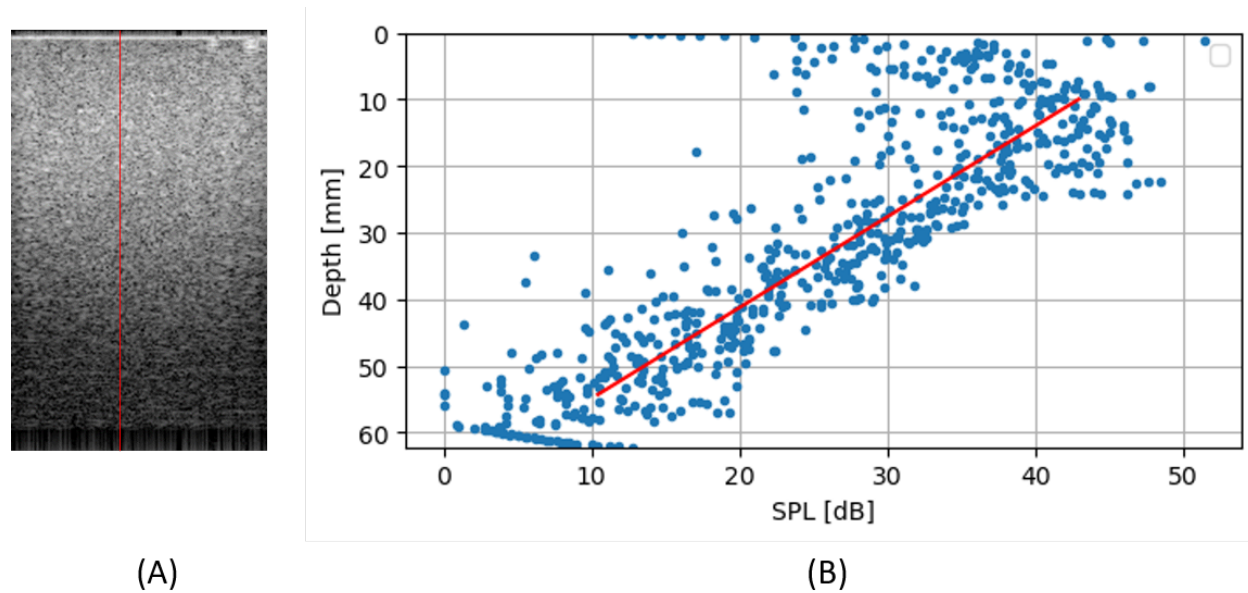


Figure 7: (A) B-mode image of mud resulting in a speckle pattern. (B) SPL plot of the vertical profile indicated with the red line in Fig. 7A.

This procedure results in a value for acoustic attenuation for each pixel column. As the picture presented as Fig. 7A has a width of 140 pixels, one picture results in 140 values for the acoustic attenuation. In addition, 20 to 100 images were recorded for each setup of array and mud sample. Processing all these images therefore results in a numerous amount of values for the acoustic attenuation which are averaged for each frequency step and mud density. The resulting acoustic attenuation values per mud density are presented in Fig. 8.

B. THROUGH-TRANSMISSION

As elaborated in Section 1, the through-transmission technique is a straight forward technique to assess the attenuation of a liquid. It uses two transducers positioned opposite to each other while submerged in the liquid (Fig. 1A). One transducer transmits the ultrasound waves while the other transducer receives. Based on Eq. 3, the received signals for the through-transmission technique can be expressed as:

$$A_R = A_0 \cdot P_m \quad (7)$$

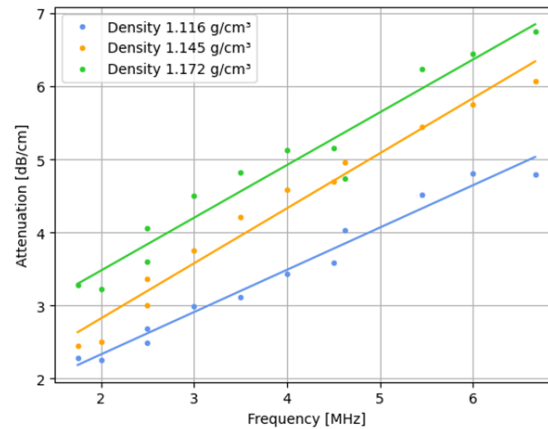


Figure 8: Final results for acoustic attenuation determined with use of medical ultrasound scanners.

Where A_R is the amplitude of the reflected signal [V], A_0 is the amplitude of the emitted signal [V] and P_m the propagation loss due to attenuation by the mud [-]. The received signal after propagation through the mud is compared to the signal received when the transducers are submerged in water. The latter is practically equal to A_0 due to the low acoustic attenuation of water.¹² From the ratio with the reference signal in water a value for the propagation loss in mud P_m can therefore be deduced. In turn this allows to determine the acoustic attenuation α_m using Eq. 4.

i. Admodus USP pro

The Admodus USP pro is an in situ measuring probe developed by Synergetik GmbH.³² It is used in harbours and waterways to determine the density profile of the mud layers at the bottom of navigation channels.^{33,34} Measurements are taken during gravitational sinking in the water and underlying mud layers. Temperature, speed of sound, acoustic impedance and acoustic attenuation are measured, creating a depth profile for each of these properties. For density profiling the measured attenuation values are not used. Its measurement is however already foreseen in case a link is found between attenuation and rheological properties of mud, as established for similar fluids.²¹ The attenuation is measured using the through-transmission technique. The two transducers used have a centre frequency of 2.25 MHz and a fractional bandwidth of 50 %, corresponding to a bandwidth of 1.69 MHz to 2.81 MHz. The output of the attenuation is however given over a broader frequency band of 1.0 MHz to 3.5 MHz in steps of 0.5 MHz. A survey campaign was performed in February 2019 in the Port of Zeebrugge, where measurements were performed at multiple locations.³⁵ The average recordings for attenuation are presented in Fig. 9. Again a linear relation is found within the fractional bandwidth of the transducers. Outside the fractional bandwidth the relation is no longer linear, especially at lower frequencies. Based on the outcome of the previously discussed experiments this non-linear relation is considered to be incorrect, neglecting the recorded attenuation values at 1 MHz.

C. BENCHMARK OF ALTERNATIVE EXPERIMENT RESULTS

All results for acoustic attenuation from the alternative experiments described in Section 3 are depicted in Fig. 10, together with the results of Section 2 as reference. Only the results of the experiments in mud with density $1145 \text{ kg} \cdot \text{m}^{-3}$ are presented. The trends and correlations between the different curves are however similar for all mud samples. The results of the experiments using the Aquascap 1000R match best with the reference values ($R^2 = 0.74$). The results of the Admodus USP pro show an underestimation of the acoustic attenuation. Unlike the other experiments, these measurements were performed on-site,

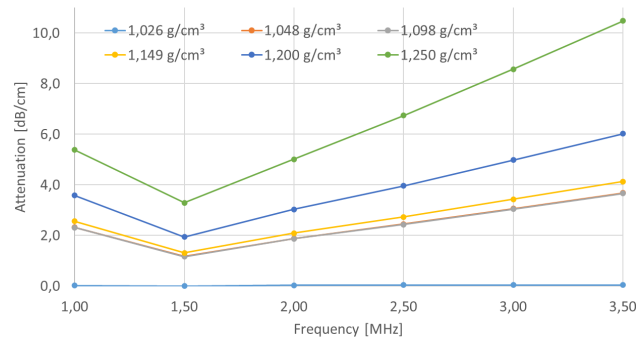


Figure 9: Averaged results for acoustic attenuation from a survey campaign in the Port of Zeebrugge, using the Admodus USP pro.

in unconditioned mud. As the the mud has the same origin, the anomalous results can be considered a confirmation of the relationship between rheological properties and acoustic attenuation as addressed in Section 1. The outcome of the B-mode experiments show both an underestimation as a different rate of increase in acoustic attenuation with increasing frequency. This mismatch for the B-mode experiments is probably caused by the design of the transducers. The other devices all have single transducers with large piezoelectric elements. Medical ultrasound scanners however use arrays which consist of multiple small transducers activated together or in a controlled sequence. While they provide high axial resolution they are less sensitive.²⁸ Hence they are less suitable for recording small differences in low signal amplitudes.

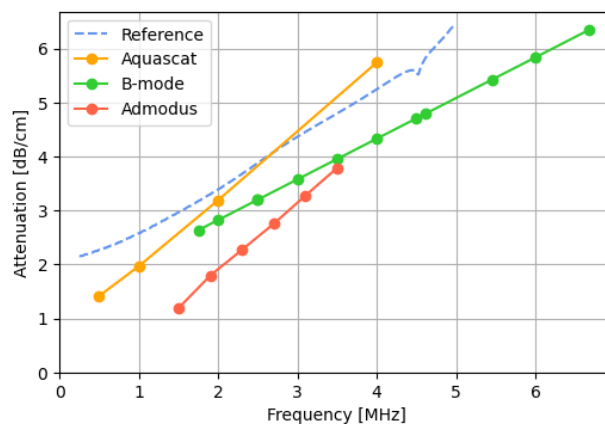


Figure 10: Plot of all results for acoustic attenuation of mud with density $1145 \text{ kg} \cdot \text{m}^{-3}$ for all alternative experiments together with the reference values (blue dashed curve).

4. CONCLUSION

By means of lab experiments the acoustic attenuation of mud has been determined in function of ultrasound frequency and for different mud densities. Furthermore, an empirical formula representing the relation between the three parameters was defined, matching well with the output of the experiments. The generated data will be of use for various topics of mud related research. The main incentive for this paper is the further development of ultrasound speckle tracking in mud. The presented results will assist in determining the optimal operating ultrasound frequency to maximize penetration depth while preserving adequate speckle image quality. In addition, the results can be of use in determining the relation between acoustic attenuation

and rheologic properties. In the end this may lead to a technique for on-site monitoring of the rheological properties of mud, which would be of great value for port and waterway authorities. A known method to determine the acoustic attenuation of fluids was applied in the lab experiments using immersible ultrasound transducers. By using two different methods of processing, it was however shown that, when at rest, mud can't be considered as a homogeneous fluid. While the conventional method assumes a homogeneous fluid, this is not applicable for mud due to its changing properties with time. On the other hand, the applied alternative processing method suffers from higher error propagation due to the requirement of results from multiple measurements. The average of the two is therefore considered as the best assessment for now. For similar experiments in the future it is advised to conduct the ultrasound scans while preventing sedimentation of the conditioned mud. This can be achieved, for example, by continuous mixing while performing the ultrasonic scans. For this option, the impact of flow velocity on the recordings should however be considered. On a general note, only results for frequencies within the fractional bandwidth should be taken into account as reliability of the measurements deteriorate drastically outside this bandwidth. A second series of experiments showed that other acoustic devices, developed for various applications, can be used for a first quick assessment of the acoustic attenuation of a liquid. A good understanding of the original application of the device and the associated specifications of the transducers is however recommended to fully appreciate the outcome of such measurements.

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