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Creating a collimated ultrasound beam in highly attenuating fluids

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ABSTRACT

We have devised a method, based on a parametric array concept, to create a low-frequency (300–500 kHz) collimated ultrasound beam in fluids highly attenuating to sound. This collimated beam serves as the basis for designing an ultrasound visualization system that can be used in the oil exploration industry for down-hole imaging in drilling fluids. We present the results of two different approaches to generating a collimated beam in three types of highly attenuating drilling mud. In the first approach, the drilling mud itself was used as a nonlinear mixing medium to create a parametric array. However, the short absorption length in mud limits the mixing length and, consequently, the resulting beam is weak and broad. In the second improved approach, the beam generation process was confined to a separate "frequency mixing tube" that contained an acoustically non-linear, low attenuation medium (e.g., water) that allowed establishing a usable parametric array in the mixing tube. A low-frequency collimated beam was thus created prior to its propagation into the drilling fluid. Using the latter technique, the penetration depth of the low frequency ultrasound beam in the drilling fluid was significantly extended. We also present measurements of acoustic nonlinearity in various types of drilling mud.

1. Introduction

The focus of this paper is the development of a method to establish a low-frequency collimated ultrasound beam in optically opaque drilling fluids that are highly attenuating to sound. This research finds application in the oil exploration industry where a need exists for imaging objects in drilling fluids. Drilling fluids serve a variety of functions while drilling for oil such as carrying cuttings from the hole to the surface, cleaning and cooling the drill bit, and reducing friction between the drill bit and the borehole casing by providing lubrication [1]. During drilling operations it is oftentimes necessary to lower a camera down the borehole, for instance to inspect the casing wall or to identify parts or tools that may have broken off or need to be removed from the borehole to prevent damage. The optically opaque mixture of oil, water and drilling fluid ("drilling mud") makes it impractical to use optical cameras. An alternative method consists of using a block of lead to make an imprint of the object that needs to be identified in the borehole. This imprint method is slow and its ability to provide accurate and usable information is limited.

Ultrasound imaging in highly attenuating fluids is challenging as one has to deal with conflicting requirements. For example, for high spatial resolution one requires a narrow beam that can be obtained using either high frequency ultrasound or large diameter transducers. On the other hand, deeper sound penetration requires low frequency that forces the beam to be wide as the frequency of the ultrasound beam is inversely related to the spreading angle and the penetration distance of the beam [2]. Commercially available ultrasound imaging devices (e.g., medical imagers) are not applicable for this type of application because these devices typically operate at frequencies greater than 2.5 MHz, which are attenuated quickly in the drilling fluids (see experimental evidence in Fig. 2 of this paper).

Despite being omnipresent in the oil industry, only limited data is available in the open literature on the physical and chemical characteristics of different drilling fluids. Caenn and Chillingar [1] reviewed recent advances in drilling fluid technology, including the different kinds of fluids and possible additives that can be used to augment their properties. Briscoe et al. [3] investigated the rheological properties of various aqueous bentonite suspensions at high pressures and high temperatures which resemble drilling fluids. They found that the physical properties of concentrated bentonite suspensions, in particular, the yield behavior, was sensitive to the ambient temperature and pressure. Hayman [4] measured the velocity of sound and attenuation of oil based and water based drilling fluids in the range of 0.2–0.7 MHz. He concluded that the attenuation (even at this low frequency range) is non-negligible and is a result of thermal and viscous effects. Additionally, Crowo [5] measured acoustic attenuation properties of oil based drilling fluids, and used regression analysis to derive an empirical equation for the velocity of sound and attenuation as a function of density and

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temperature. Most recently, Lan and Yan [6] studied propagation of sound in bentonite slurries in the 50–200 kHz frequency range, and confirmed that penetration depth is a function of the slurry density.

Many researchers have investigated ultrasound imaging systems. The use of linear imaging techniques with a high frequency beam to obtain the desired spatial resolution, is described in the literature [e.g., [7–9]]. Other techniques such as acoustic lenses have been studied to improve the spatial resolution of ultrasound imaging systems without increasing the beam frequency [10–12]. Few researchers have also investigated the use of a parametric array to perform ultrasound imaging, or have investigated ultrasound imaging in a highly attenuating medium. Ward et al. [13] used nonlinear propagation to improve the resolution of ultrasound imaging and Duck [14] investigated the nonlinear phenomena occurring specifically in diagnostics ultrasound. Furthermore, imaging by means of a parametric array has been exploited in the field of (sub-) sea bed visualization [e.g., [15–17]]. To the best of our knowledge, no published studies exist on using a parametric array to create an ultrasound beam in highly attenuating, opaque fluids. Furthermore, no data is available in the open literature on the acoustic nonlinearity properties of drilling fluids.

In this paper, we describe a method based on a parametric array, to create a low frequency collimated ultrasound beam in highly attenuating water based and mud based drilling fluids. We also provide experimental characterization of the physical and acoustic properties (including acoustic nonlinearity) of three different types of water based and oil based drilling fluids we have used in the parametric array measurements.

2. Drilling fluid test specimen

Different drilling fluids are used during the drilling process to accommodate a variety of drilling depths, pressures, temperatures, and to alleviate tribology problems. Traditionally, drilling fluids have been divided into four categories according to the base fluid used in their preparation: air, water, oil, and synthetic drilling fluids [1]. While oil based drilling fluids are known for superior temperature stability and lubricity, most of the oil drilling operations use water based and synthetic based drilling fluids for ecological reasons. Usually, different additives are mixed with the drilling fluids to enhance specific properties, such as reducing the friction coefficient [1].

We have measured the physical properties of a water based drilling fluid (WBM) and two synthetic based drilling fluids (SBM) of different density, with water as a benchmark. Table 1 shows the density and the sound speed of the different fluids. The density was obtained using a weight and volume measurement, and verified with a densimeter. The sound speed was measured using a pulse echo time-of-flight measurement (frequency of 3.1 MHz) over a calibrated distance (20 mm). All measurements were performed under atmospheric conditions.

Table 1 confirms that the drilling fluids are more dense than water, and that the sound speed in the drilling fluids we have used decreases with increasing density. Fig. 1 shows the viscosity η as a function of temperature T (from 25 to 50°C) for the drilling fluids (Fig. 1a) and for water as comparison (Fig. 1b). The viscosity results were obtained using a vibro-viscometer (AND Ltd., SV-10), and averaged over three measurements. A linear best-fit for the averaged results is shown in the respective figures.

From Fig. 1a and b we observe that the viscosity decreases monotonically with increasing temperature. The viscosity of the drilling fluids is two orders of magnitude higher than the viscosity of water. Fig. 2 illustrates the attenuation of the different media and shows the normalized sound pressure at a frequency of 3.1 MHz (ratio of local and maximum sound pressure) as a function of penetration distance in the medium, along the longitudinal center axis of the ultrasound transducer.

From Fig. 2, we observe that the drilling fluids are significantly more attenuating to sound than water. While Fig. 2 shows data obtained at a frequency of 3.1 MHz (this frequency is later used in Section 2 of this paper), we observed this to be the case over the entire frequency spectrum. Additionally, the water based drilling fluid allows sound to penetrate (maximum normalized pressure at approximately 30 mm) further than the synthetic based drilling fluids (maximum normalized pressure at 5 mm (SBM10) and 0 mm (SBM15), respectively). Based on the sound pressure measurement, a transition from near field to far field can be estimated in the case of WBM10, approximately at 40 mm from the source along the transducer axis. This measurement is relevant for the parametric array studies described later.

Finally, we have determined the degree of acoustic nonlinearity of the drilling fluids using the "finite displacement approach" described in Appendix A. Table 2 shows the results for the nonlinearity factor β and B/A, where $\beta = 1 + B/2A$, with A and B the coefficients of the first and second order terms of the Taylor expansion of the equation relating the material's pressure to its density.

Table 1
Physical properties of different drilling fluid specimen.

Type	Density (kg/m^3)	Sound speed (m/s)
Water	1000	1500
WBM10	1180	1540
SBM10	1170	1430
SBM15	1760	1250

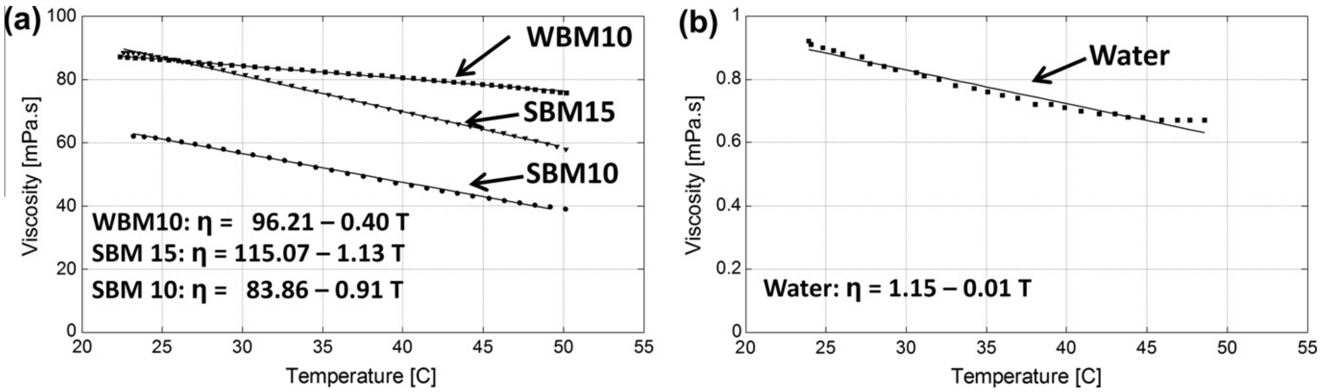

Fig. 1. Viscosity versus temperature for (a) drilling fluids and (b) water.

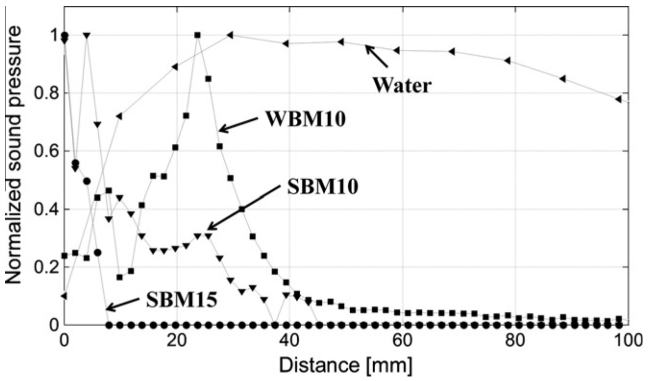

Fig. 2. Sound attenuation at 3.1 MHz as a function of penetration distance, normalized by the maximum sound pressure at the source.

Table 2
Measure of nonlinearity.

Type	β	B/A
Water	3.5	5
WBM10	5.5	9
SBM10	5	8
SBM15	N/A	N/A

These results are the average of three independent, repeatable measurements.

We did not successfully obtain a reliable and accurate measurement of β for the SBM15 drilling fluid, because the sound did not penetrate far enough through the medium to provide an accurate measurement. From Table 2, we observe that the drilling fluids are more nonlinear than the water benchmark, which is important in light of using a parametric array to create a low frequency focused acoustic beam, as will be discussed further in this paper.

3. Using drilling fluids as nonlinear medium for frequency mixing

The objective is to generate a collimated ultrasound beam of low frequency by the collinear mixing of two high frequency and high power primary ultrasound beams that can be used to visualize objects in drilling fluids in a nonlinear medium. The low frequency beam generated this way is the difference frequency of the two primary frequencies. While this difference frequency beam is weaker in power than the original primary beams, it is significantly more collimated than a beam produced by a traditional transducer operating at the low frequency [18,19]. Another important factor is that this low frequency beam does not show any side lobes unlike beams produced by traditional transducers, and this avoids the undesirable reflections when used for imaging purposes. Westervelt [20] calculated the pressure amplitude of the difference frequency wave as

$$p_s = \frac{(\omega_s^2 \rho_0 A/8\pi R_0)\exp(ik_s R_0 - i\omega_s t)}{i\alpha + k_s \sin^2(\theta/2)} \tag{1}$$

and $A = -\omega_s^2 \rho_0^{-2} C_0^{-4}\left[1 + \frac{1}{2}\rho_0 C_0^{-2}\left(\frac{d^2p}{d\rho^2}\right)_{\rho=\rho_0}\right] P_0^2$

Here, ω_s is the angular frequency of the difference frequency beam, $k_s = \omega_s/C_0$ is the wavenumber, C_0 is the sound speed, ρ_0 the density of the medium at atmospheric pressure, R_0 is the distance between a point in the ultrasound beam and the pressure source, t is the time, α is the attenuation coefficient, P_0 is the pressure amplitude of the acoustic source, and ρ and p are the local density and pressure in the medium, respectively. r and θ are the coordinates in a cylindrical coordinate system. The collimation of the difference frequency wave can be seen from Eq. (1). When the angular coordinate θ increases (deviates from $\theta = 0$), the pressure decreases as a function of $\sin^2(\theta/2)$.

3.1. Apparatus

Fig. 3 shows the experimental apparatus used for the beam profile measurements. A piezoelectric disk transducer (PZT-5, 3.1 MHz center-frequency and 25 mm in diameter) was fixed inside a Plexiglas tank filled with the drilling fluids studied and served as the pressure source. A receiver transducer (PZT-5, 500 kHz center-frequency, 15 mm in diameter) was mounted to a motorized linear *X–Y* stage facing the source transmitter and was used to scan a rectangular pattern with a step-size of 5 mm in both *X–Y* directions to determine the beam profile. At each point of the scan pattern, the acoustic pressure was recorded and averaged over 32 measurements. The axis of the source and receiver transducers remained in the same plane parallel to each other, and parallel to the bottom of the tank.

The source transducer was simultaneously excited by two primary frequencies in the neighborhood of the center frequency but with two slightly different frequencies. This allowed the creation of a difference frequency Δf in the range of 300–500 kHz and this did not exceed 15-to-1 step-down ratio from the primary frequency for efficient generation of the difference frequency beam [21]. The 500 kHz center frequency receiver was insensitive to the primary frequency beam to a large extent, but almost equally sensitive in the 300–500 kHz range, as a result of a low q-factor. The output voltage of the receiver was calibrated with a calibrated hydrophone (ONDA Corp. HNR-1000, diameter 1.5 mm) to convert voltages into sound pressures.

The source transducer was driven by a frequency generator with two individually adjusted outputs and this was first amplified by a 50 dB power amplifier before feeding to the transducer. The receiver output signal was band pass filtered and amplified by a 40 dB amplifier prior to capturing the data with a data acquisition system (DAQ). For the source excitation, we used a sine-wave toneburst of 20 μs in duration, to avoid interference and to be able to determine the time of flight unambiguously.

3.2. Experimental results

Fig. 4 shows the experimental results with the drilling fluid used as a nonlinear medium to obtain the low frequency collimated beam. The results are shown for the three different drilling fluids in the vertical direction and for three different difference frequencies in the horizontal direction. Only the difference frequency beam is shown as the output signal from the receiver transducer was band pass filtered at $\Delta f \pm 100$ kHz, where Δf is the difference

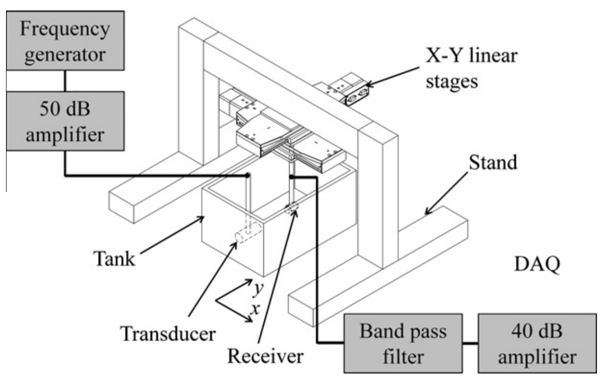

Fig. 3. Apparatus for creating an ultrasound beam in drilling fluids.

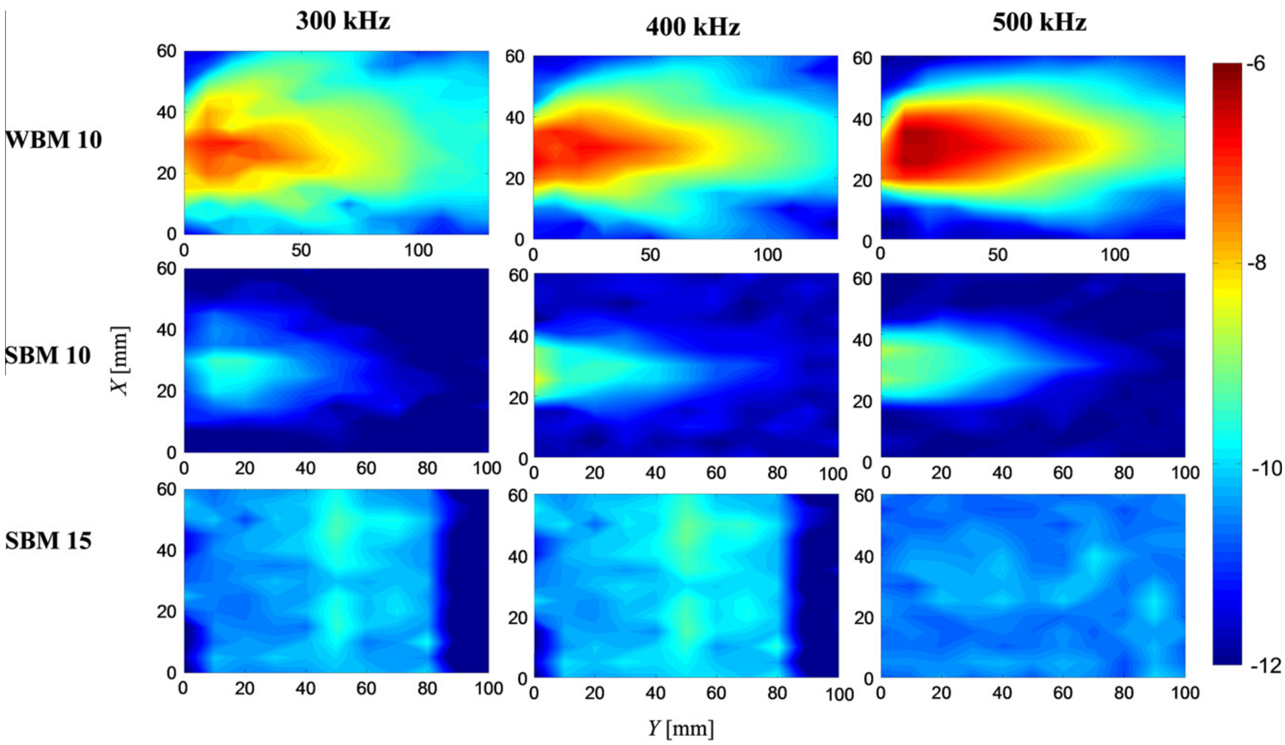

Fig. 4. Logarithmic acoustic pressure of the difference frequency ultrasound beam in drilling fluids, using the drilling fluid as a nonlinear medium.

frequency between the two primary frequencies that were superimposed and used to excite the transducer. The following pairs of primary frequencies were used to obtain the desired difference frequencies: 3.1 MHz and 3.4 MHz, 3.1 MHz and 3.5 MHz, 3.0 MHz and 3.5 MHz, for difference frequencies of $\Delta f = 300$ kHz, 400 kHz and 500 kHz, respectively. In Fig. 4, the logarithm of the acoustic pressure of the difference frequency beam is shown as a function of x and y coordinates (top view of tank in Fig. 3, with y the axial direction of the transducer, as indicated) normalized with the maximum acoustic pressure of the lowest primary frequency at the piston source. The maximum acoustic pressure was determined for the different primary frequencies with a calibrated hydrophone (see Table 3).

From Fig. 4 we observe that only in the WBM10 drilling fluid, a collimated beam could be obtained. Significant divergence of the beam can be seen for the case of a difference frequency of 300 kHz. We were unable to clearly observe the collimated beam in the synthetic based drilling fluids SBM10 due to the high frequencies used for the primary beams which correspondingly are attenuated quickly before generating an observable difference frequency. We also did not observe any significantly collimated beam in the SBM15 drilling fluid as well for the same reason.

4. Mixing tube

To circumvent the problem of high attenuation and the resulting short mixing length in drilling fluids, an altogether different approach was pursued. This improved approach consists of separating the formation of an ultrasound beam from the medium (drilling fluid) one attempts to create the beam in. A separate mixing tube containing a nonlinear medium that is minimally attenuating to sound can be used to host the frequency mixing process and create a low frequency collimated beam. This mixing tube approach was originally demonstrated by Bjørnø [18] and Ryder [19], and we have adapted this approach for this particular application.

Table 3
Source pressure.

Frequency (MHz)	Source pressure (kPa)
3.0	230.7
3.1	293.8
3.4	211.6
3.5	198.3

4.1. Apparatus

The improved apparatus is shown in Fig. 5 and is identical to the apparatus in Fig. 3 with the addition of a Plexiglas mixing tube of thickness 3 mm to separate the transducer from the drilling fluid. The parametric array is now created inside the mixing tube, and the mixing length to establish the parametric array depends on the degree of nonlinearity of the medium used, and decreases with increasing B/A or β. In the present case, the mixing tube contains

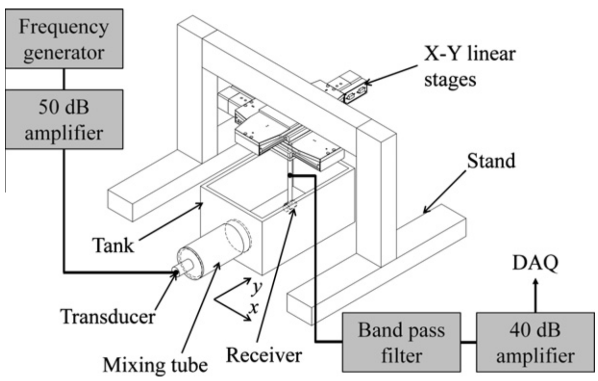

Fig. 5. Apparatus for creating an ultrasound beam in drilling fluids with mixing tube.

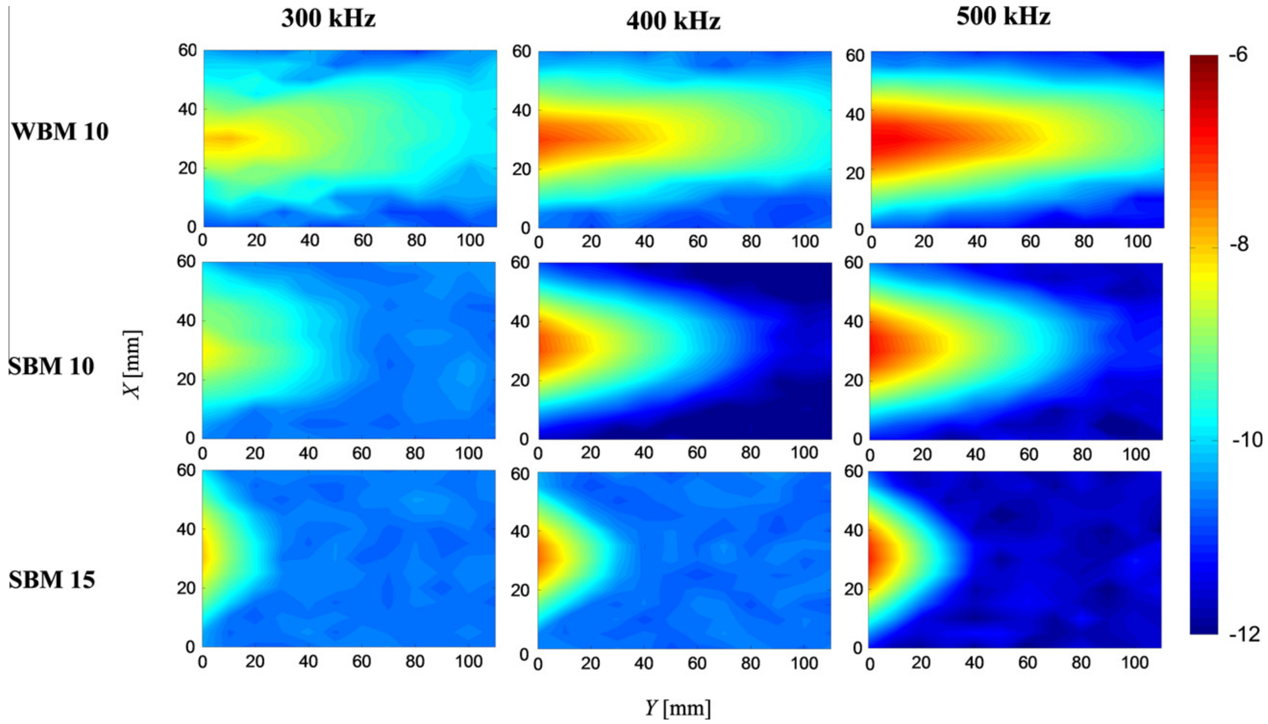

Fig. 6. Logarithmic acoustic pressure of the difference frequency ultrasound beam in drilling fluids, using water as a nonlinear medium in mixing tube.

Table 4
Penetration depth of ultrasound beam in drilling fluid using a mixing tube.

Type	Without mixing tube			With mixing tube		
	300 kHz	400 kHz	500 kHz	300 kHz	400 kHz	500 kHz
WBM10	>120 mm	>120 mm	>120 mm	>120 mm	>120 mm	>120 mm
SBM10	40 mm	60 mm	70 mm	60 mm	80 mm	90 mm
SBM15	0	0	0	25 mm	30 mm	40 mm

water, which is nonlinear and does not attenuate sound significantly over the short distance in the apparatus. By visualizing the ultrasound beam profiles for the difference frequency beam of the parametric array in water, the distance for which maximum sound pressure (mixing length) is obtained was determined to be 130 mm. Hence, the mixing tube was sized to obtain maximum sound pressure at the end of the tube, where the low frequency collimated beam transfers into the drilling fluid.

We have used an identical transducer and receiver as the ones used for the apparatus in Fig. 3. The scanning pattern of the receiver was identical as well with a pitch of 5 mm in both x and y directions.

4.2. Experimental results

Fig. 6 shows the experimental results with the mixing tube apparatus (Fig. 5) for the three different drilling fluids in the vertical direction and for three different difference frequencies in the horizontal direction. The same primary frequencies were used to obtain the 300 kHz, 400 kHz and 500 kHz difference frequencies than the ones used to obtain the results shown in Fig. 4. In Fig. 6 the logarithm of the acoustic pressure of the difference frequency beam is shown as a function of x and y coordinates (top view of tank in Fig. 5), normalized with the maximum acoustic pressure of the primary frequencies at the piston source, and measured with a calibrated hydrophone.

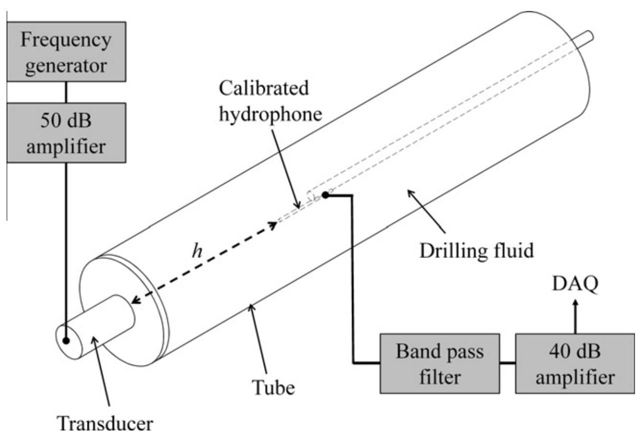

Fig. A1. Determining β of a nonlinear medium using the finite amplitude approach.

From Fig. 6 we observe that in all three tested drilling fluids, a significantly more collimated low frequency beam with increased penetration distance could be obtained compared to the experiments without the mixing tube. The results show that even in the synthetic based drilling fluids (SBM10 and SBM15) a collimated low frequency ultrasound beam can be established.

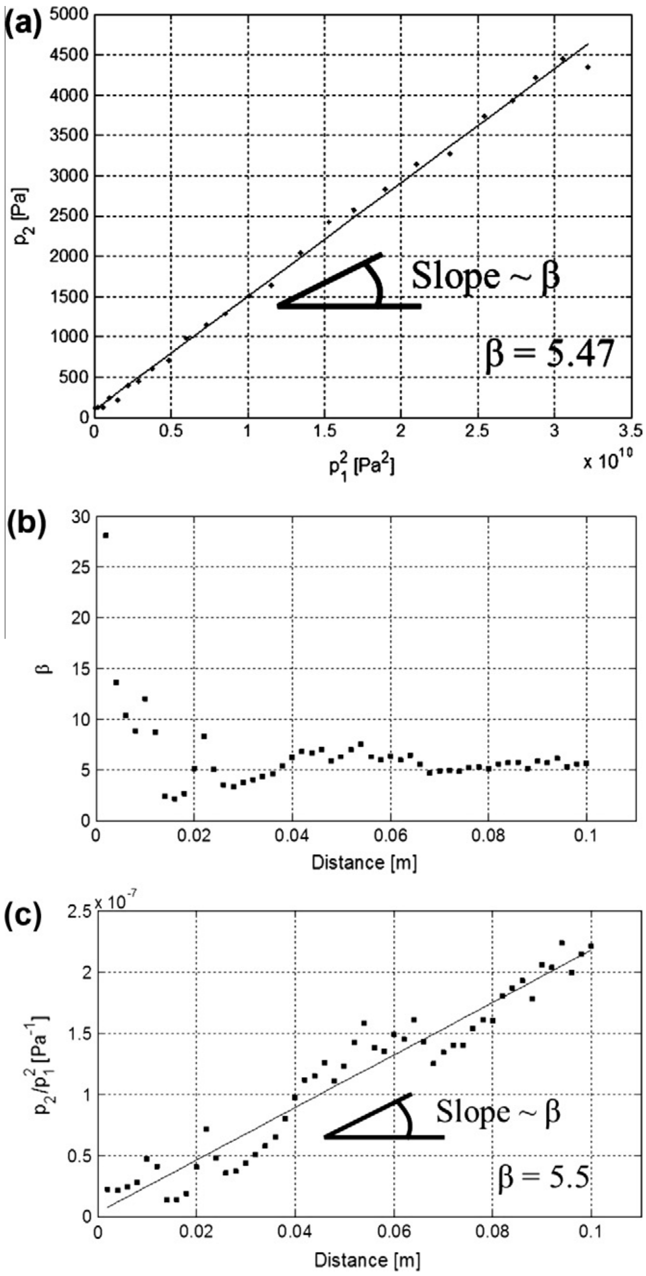

Fig. A2. (a) Determining β at a specific distance h from the transducer, (b) β as a function of the distance h from the transducer, and (c) calculating an average β.

5. Discussion

When creating a parametric array in a nonlinear medium, the required mixing length [16–19] can be calculated as the minimum of the shock distance $R_s = \lambda_p/2\pi\beta M$, the absorption distance $R_a = 1/\alpha$ and the Rayleigh distance $R_F = d^2/\lambda_p$, where λ_p is the wavelength of the primary frequency, β is the nonlinearity parameter, M is the Mach number, α is the absorption coefficient and d is the diameter of the transducer. The primary frequencies, which are an order of magnitude higher than the resulting difference frequency, are attenuated much faster by the drilling fluid. The experimental results (Fig. 3) suggest that the primary frequencies do not penetrate sufficiently through the drilling fluid to achieve the required mixing length and create the parametric array, i.e., the parametric array is limited by the absorption length that is significantly shorter that the Rayleigh length. This is particularly true for the SBM10 fluid, in which only a low intensity collimated beam is formed compared to the WBM10 fluid, and the SBM15 fluid where no collimated beam is formed.

Using a mixing tube with a nonlinear, non-attenuating medium (water) rather than using the drilling fluid as a nonlinear medium decouples the beam formation from the medium one is creating the beam in. The length of the mixing tube depends on the nonlinear medium in the tube. In the case of water, we experimentally determined the beam profile and found that a length of 130 mm is optimal because the acoustic pressure of the low frequency collimated ultrasound beam was found to be maximum at this distance. The mixing tube was made of Plexiglas. It is important to choose a material for the front face through which the beam emerges that closely matches the impedance of the nonlinear medium to maximize the transmission of the beam from the mixing tube to the drilling fluid.

We observe that the ultrasound beam penetrates much further into the drilling fluid in the experiment with the mixing tube, as expected. Table 4 summarizes the penetration depth of the ultrasound beam at different difference frequencies of the parametric array, without and with the mixing tube. Not just the deeper penetration is important to point out, but also that the beam still is tightly collimated (see Fig. 6), even after transferring through different media.

6. Conclusions

We have studied the formation of a low-frequency collimated ultrasound beam in different water based and synthetic based drilling fluids. While we were able to quantify the nonlinearity of the drilling fluids, the strong attenuation inhibits the formation of a usable parametric array using the drilling fluids as host medium for practical imaging purposes. The high frequency primaries do not penetrate far enough through the drilling fluids to obtain adequate mixing and to create the collimated difference frequency component.

The use of a mixing tube, containing a nonlinear medium that is not very attenuating to sound over short distances, allows separating the formation of the low-frequency collimated beam from the actual medium one wants to image in. Using such a mixing tube, we were able to create a collimated ultrasound beam that penetrates up to 120 mm through water based drilling fluid and up to 80 mm through the more attenuating synthetic based drilling fluids.

Acknowledgements

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Appendix A. Determining β

We have determined $\beta = 1 + B/2A$ using the finite amplitude approach [21–28]. Starting from the equation of motion for plane elastic waves propagation through a medium, the degree of nonlinearity can be determined as

$$\beta = \frac{\rho_0 C_0^3}{\pi f h}\frac{p_2}{p_1^2} \tag{A1}$$

where ρ_0 is the density of the medium, C_0 is the sound speed of the medium, f is the frequency, h is the distance between the transducer and the hydrophone and p_1 and p_2 are the amplitudes of the sound pressure of the fundamental frequency and second harmonic, respectively [23].

Fig. A1 shows the apparatus we have built to measure the nonlinearity of the medium. It consists of a tube that contains the drilling fluid. The bottom of the tube fits a transducer with a center frequency of 536 kHz, driven by a frequency generator and a 50 dB amplifier. The axis of a calibrated hydrophone (ONDA Corp. HNR-1000, diameter 1.5 mm) is aligned with the axis of the transducer. The hydrophone is affixed to a displaceable rod. The pressure of the fundamental and second harmonic is determined at different distances h between transducer and hydrophone.

β can be determined from the slope of the p_2 versus p_1^2 relationship (Eq. (A1)). For short distances between the transducer and the hydrophone (within the near field) the determination of β is ambiguous due to diffraction and transducer nonlinearity. Therefore it is important to determine β at different distances h from the pressure source. Lastly, plotting p_2/p_1^2 as a function of h also allows extracting β as the slope of this plot [28]. Fig. A2 shows the results of a typical measurement for the WBM10 drilling fluid. Fig. A2a shows the pressure of the second harmonic p_2 versus the fundamental frequency p_1 at a distance of 66 mm between the transducer and the hydrophone. A linear best fit is indicated in the figure; the slope is equal to $\beta(\pi f h/\rho_0 C_0^3)$ (from Eq. (A1)), which allows to calculate $\beta = 5.47$ for $h = 66$ mm. Fig. A2b shows β as a function of the distance h, indicating large variations in β in the near field of the transducer. Fig. A2c shows p_2/p_1^2 as a function of the distance h between transducer and hydrophone. A linear best fit is again indicated in the figure. The slope is equal to $\beta\pi f/\rho_0 C_0^3$, which allows calculating an average value of $\beta = 5.5$.

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