Rheological Characterization of non-Newtonian Drilling Fluids with non-invasive Ultrasonic Interrogation

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Abstract*—The drilling process is generally costly and time consuming and prone to serious hazards. Cost-efficiency and enhanced safety measures are vital for any drilling operation. Recent studies indicate that poor reliability in the drilling process resulted in as much as 30% loss of production time. Improved sensor technology with process automation can improve process performance and safety. During drilling operations, along with the drillstring, a drilling fluid, commonly very dense and viscous fluid, is circulated in a closed flow-loop. The drilling fluid, non-Newtonian in its rheological behavior, serves three main objectives: keeping the bottom-hole pressure at an acceptable level, lubricating the drill bit and facilitating the removal of cuttings and debris from downhole. These three goals have to be kept in balance and are achieved by adjusting the density (ρ), viscosity (μ) and the flow-rate (q_v) of the drilling fluid. These three drilling process parameters need to be continuously monitored for optimizing process performance and securing safety. The cuttings in the drilling fluids make it especially challenging when conventional in-line sensor systems are used due to the unavoidable erosion and maintenance costs. Non-invasive ultrasonic measurement techniques can be part of a robust and easily implementable control and monitoring system. In this work ultrasonic properties of different drilling fluids are studied. Propagational properties of different samples of drilling fluids are studied with focus on attenuation and frequency characteristics in transmission mode. Experimental results using different sets of ultrasonic transducers with different frequencies, confirm the high attenuation of ultrasonic pulses. A model is proposed to estimate the attenuation and viscosity of the drilling fluid based on ultrasonic and rheological parameters. This study presents results from ultrasonic interrogation of non-Newtonian fluids with focus on their rheological properties.

***Keywords*— Ultrasonic attenuation; Drilling fluid; Drilling fluid viscosity, Drilling fluid density, non-Newtonian fluid**

I. INTRODUCTION

The process of drilling oil & gas wells either on land or offshore, uses a special drilling fluid for several purposes. The drilling fluid is circulated through a flow loop which extends from the surface equipment down to the drill bit in the bore hole. Some of the more important purposes of the drilling fluids are: Controlling the bottomhole pressure (BHP); cool, lubricate and clean the drill bit; and remove rock cuttings from the well [1], [2].

These and other characteristics of drilling fluids require them to possess conflicting chemical and physical properties. These conflicting requirements lead to challenges to the engineers involved in their production. The drilling fluid can be either water based mud (WBM) or oil based mud (OBM), satisfying environmental regulations and possessing specific rheological properties. Several additives are used to tune the drilling fluid to achieve the set of desired properties necessary for a particular application. Drilling fluids with their high viscosities and high densities are non-Newtonian in their rheological behavior and help to carry the cuttings from the borehole to the surface.

Online access to the rheological parameters of the drilling fluid and its behavior during its circulation in the flow loop is useful for the optimal operation of the rig. The drilling fluid is designed, mixed and checked before being fed into the circulation. During the drilling operation, properties of the drilling fluid changes continuously. The drilling engineer has to rely on various measurements based on samples taken at specific locations in the circulation system, including intermittent lab-analysis. Hence, dedicated non-invasive online measurement techniques would improve the monitoring of rheological properties. Monitoring the drilling fluid properties is important for safety reasons, but also for maintaining and improving the drilling efficiency.

In this study, we have investigated the relationship between ultrasonic and rheological properties of the drilling fluid. By combining empirical models with ultrasonic measurements of the mud returning from the wellbore, we can better understand the behavior of the drilling fluid. This will ensure that the drilling fluid keeps its properties as desired, and thus performs according to expectations.

Ultrasonic measurements are one of the measurement principles to be applied to the drilling fluid during its return flow. This is a non-intrusive measurement of selected characteristics on the drilling fluid, and measurements of ultrasonic properties of drilling fluid have been shown to be correlated to fluid properties such as density and viscosity[3]–[5].Ultrasonic measurement techniques are already used in flow-metering of various oil, gas and multiphase streams in the petroleum industries. Flow meters using transit-time difference and Doppler frequency-shift are already in use in the field [6]. We wanted to explore further the possible uses of ultrasonic measurement principles to determine the rheological properties of drilling fluids. A similar study [7] in the food industries has shown very good results in characterizing another complex fluid, the well-known tomato ketchup, which is also non-

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Newtonian. Similar attempts have been made in characterizing slurries, another complex fluid found frequently in the process industries [8]. The aim of the current study is to model the rheological properties that are hard to measure online, by using the ultrasonic properties.

II. EXPERIMENTAL METHODS

A. *Ultrasonic measurements*

Data for the developed models have been collected at University College of Southeast Norway (USN). The setup was developed and used as a part of a final year project at USN [9], and further developed for collecting data for this study. The measurements were taken in a tank, with capacity of 170 liters. Transmission mode of ultrasonic wave propagation was used in the tests with transmitter and receiver submerged in the drilling fluid, both mounted on a rack and guided using a rail above the tank, as shown in Fig. 1. This rack and rail arrangement is used to adjust the linear spacing *x* between the transmitter and receiver. The ultrasonic attenuation and transit-time were recorded at each location, as the spacing was stepwise increased.

We used three transducer couples in through transmission mode. All with the same dimensions, 2.54 cm (1 in) element diameter, and three frequencies; 0.5, 1.0 and 2.25 MHz. The attenuations measured at a 3 cm linear spacing were used as references (0 dB) for the three different transducer couples. The linear spacing was stepwise increased in 2 cm increments. The measurements were repeated to add to the data available for facilitating the development of a suitable model development.

B. *Mud analysis*

The drilling fluid used in these experiments was produced by MI Swaco, and supplied by Statoil for the purpose of these measurements. To relate the rheological and ultrasonic properties, it was decided to gradually dilute the supplied sample. We started out with the drilling fluid as it was supplied, and in steps diluted it five volume percentage 10 times with water. This gave us ultrasonic measurements on 11 different fluids, which then had the same components, but with different concentrations and therefore different rheological properties. The fluids will be referred to as Fluid 1 through Fluid 11. For Fluid 1 and 2, only two samples for mud analysis were collected, for the remaining fluids the results of the mud analysis are from 4 samples. Extensive fluid analysis on the sample fluids, with focus on rheological properties, was done at Statoil. The methods used in this analysis are comparable to, but are not exactly the same as those used in the field analysis of drilling fluid. This limits the comparability of the results from our analysis of the mud to the results from other drilling fluid analysis. For our purpose, they serve very well, as they allow us to compare the attenuation with the changes in specific rheological properties. The rheological properties analyzed are density, viscosity, gel strength and yield point. Since the sample fluids are non-Newtonian, the viscosity is dependent on the shear rate, and a single value will not describe the fluid. The established practice in drilling is then to use a Bingham-Plastic model to describe the viscosity, and the reference viscosity is known as plastic viscosity (PV) [1]. The initial yield stress needed to start the flow of fluid, known as the yield point, is one of the main characteristics of non-Newtonian fluids. The Bingham-Plastic model for non-Newtonian fluids are described by the equation,

$$\tau = \mu_p \dot{\gamma} + \tau_y \tag{1}$$

where the parameters are: τ – shear stress [Pa]; μ_p – the plastic viscosity [Pas] ; $\dot{\gamma}$ – the shear rate [1/s]; τ_y – yield point [Pa].

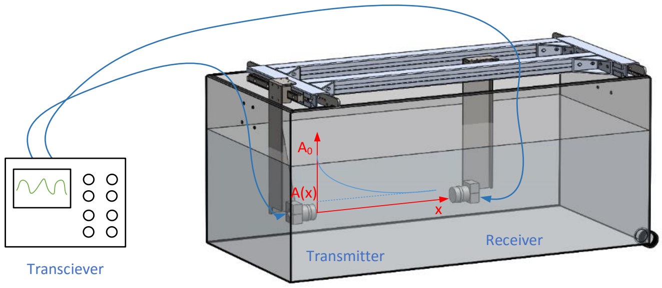


Fig. 1: Ultrasonic experimental setup with transmitter and receiver submerged in a tank containing the drilling fluid. *x* is the linear spacing between transmitter and receiver

III. RESULTS AND DISCUSSION

A. *Ultrasonic attenuation*

For the ultrasonic data, we recorded the time of flight (ToF) and the received amplitude [dB]. Using these measurements, we calculated the relative amplitude. Fig. 2 shows the relative amplitude, *A(x)* [dB] against the distance, *x* [cm] between the transmitter and receiver for all 11 fluids used in this study, with the three different frequencies. We can observe two important characteristics for the fluids and the ultrasonic attenuation here. First, we see that the attenuation in dB for each fluid appears linearly dependent on the distance. Secondly, the order the curves stack on each other is the same order the fluids were diluted from fluid 1, as the slope of the curves is increasing with decreasing density, which implies positive correlation between density and attenuation coefficient. Furthermore, the spacing between them indicate there is a close relationship between the changing properties of the fluids, and the decreasing slope (attenuation) of the curves.

With this, we could anticipate that the diluting process had changed the fluid in such a way that the attenuation decreased as well. We used a linear least squares method on measurements in dB scale to determine α based on the model for reduced amplitude [10]–[12], as in

$$A(x) = A_0 e^{-\alpha x} \tag{2}$$

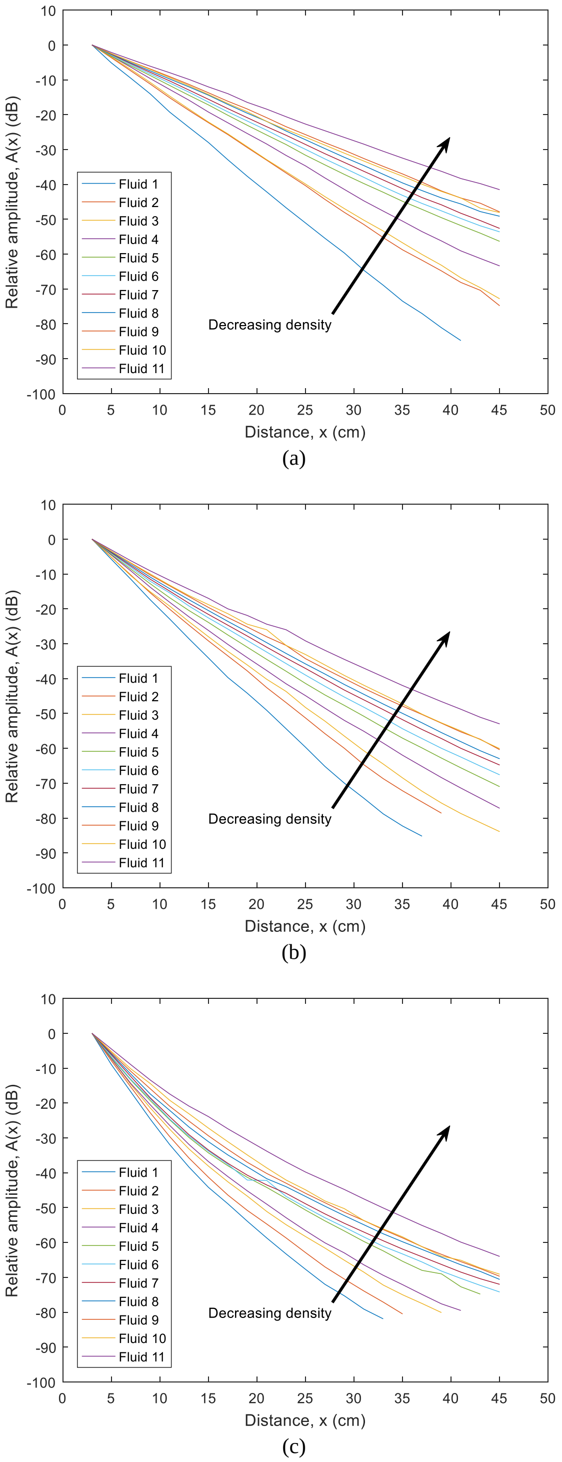
where the parameters are: A – reduced amplitude [V]; A_0 – unattenuated amplitude [V] at $x = 0$; α – attenuation coefficient [Np/m]; x – propagation distance as shown in Fig. 1 [m].

Now, with the data shown in Fig. 2 we can develop the regression models as outlined in (2) for each fluid sample, for each frequency. This gives an estimate of α, which we can compare for all fluid samples, given the frequency.

B. *Regression models*

The ultrasonic measurements clearly indicated that there is a close relationship with the decreasing density of the fluid samples and the ultrasonic attenuation. With the rheological lab measurements, we can relate this change in attenuation to rheological properties. We used linear least squares methods on the lab measurements for density and viscosity together with the estimated attenuation coefficient. This gave some promising models for these rheological properties, based on the ultrasonic properties. Regression plots of the models are shown in Fig. 3, in total six models are presented. Table 1 shows the model coefficients as in (3) as well as R^2 and RMSE (Root Mean Square Error) for fit evaluation.

$$[\rho \quad \mu_p] = \begin{bmatrix} a_\rho & b_\rho \\ a_{\mu_p} & b_{\mu_p} \end{bmatrix} \begin{bmatrix} \alpha \\ 1 \end{bmatrix} \tag{3}$$

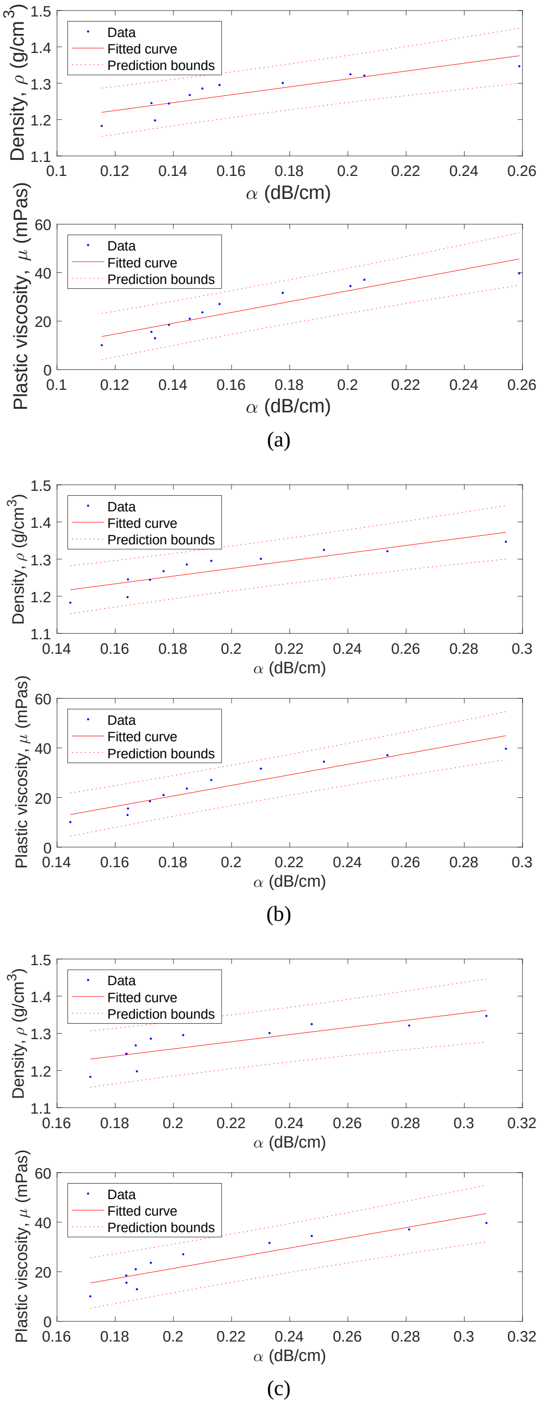


(a)

(b)

(c)

Fig. 2: Relative amplitude for 11 fluids plotted against linear spacing of the transmitter and receiver. Signal frequency is 0.5 MHz (a), 1.0 MHz (b) and 2.25 MHz (c).Where the curves end for shorter distances than 45 cm, attenuation resulted in an unrecognizable amplitude.



(a)

(b)

(c)

Fig. 3: Regression models for density and plastic viscosity. (a) for 0.5 MHz, (b) for 1.0 MHz and (c) for 2.25 MHz.

These results are varying in fit quality, and albeit showing potential, we believe that non-linear models, and combing more inputs will lead to improved models. One model may describe all available data for the different fluids. Both the lab measurements of the drilling fluid as well as the ultrasonic measurements are extensive and include more data than we could use for analysis in this paper. Preliminary studies looking into the development of non-linear empirical models with data fusion of measured sound velocity as well as measured attenuation indicate that such models can give reliable estimates of density or viscosity. A sketch for realizing such a data fusion scenario is shown in Fig. 4. Similar to the matrix equation (3) above, the model can fuse the times of flight yielding velocity of sound in real time thus enabling a continuation evaluation of the density and plastic viscosity in the process. Such a real time estimate will help to trace trends and alleviate extraordinary and dangerous process scenarios such as blowouts.

IV. CONCLUSION

In this study we have made extensive and numerous ultrasonic measurements on 11 samples of drilling fluid. Equally extensive lab measurements were made on the same 11 samples. This has provided large amounts of ultrasonic data and data on rheological properties to be analyzed for correlation. The first analyses are presented in this publication. Applying linear least squares method on the ultrasonic data yielded good results in estimating the attenuation coefficients for the different fluids, using three frequencies: 0.5 MHz, 1.0 MHz and 2.25 MHz. The linear trend was better with lower frequency. The experimental results show positive correlations between both attenuation and density, and between attenuation and plastic viscosity. However, the relationships are only fairly described by linear models, with R^2 values between 0.69-0.89. Further analyses will focus on more data fusion and non-linear empirical models, e.g. artificial neural networks.

TABLE 1: REGRESSION MODEL COEFFICIENTS AND FIT EVALUATION VALUES.

Model	**Density, ρ [g/cm^3]**			**Viscosity, μ_p [mPas]**		
	0.5 MHz	***1.0 MHz***	***2.25 MHz***	***0.5 MHz***	***1.0 MHz***	***2.25 MHz***
a	1.08	1.03	0.96	223	213	206
b	*1.10*	1.07	1.1	-12	-18	-20
R^2	0.77	0.78	0.69	0.87	0.89	0.85
RMSE	0.03	0.03	0.03	3.8	3.4	4.1

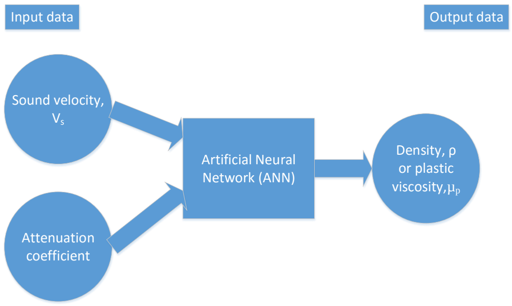


Fig. 4: Sketch of future planned empirical model with data fusion on input and rheological properties as output.

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