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Research on ultrasonic-based drilling fluid viscosity detection method

Chaoyang Xiang*. Mingjiang Shi
School of Mechanical Engineering, Southwest Petroleum University, Chengdu, China
Email: 172729946@qq.com

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Abstract

Drilling fluid viscosity directly affects the efficiency and safety of drilling op-erations. Proper viscosity can ensure that the drilling fluid can effectively carry drill cuttings and maintain the stability of the well wall. Therefore, real-time and accurate viscosity measurement of drilling fluid is crucial to ensure the safety of drilling operation and improve the production efficiency. The article proposes a method to measure the viscosity of drilling fluid based on ultrasonic attenuation method. Firstly, an experimental device for ultrasonic drilling fluid viscosity detection was designed and an experimental platform for ultrasonic drilling fluid viscosity detection was constructed. Secondly, the propagation and attenuation of ultrasonic waves in drilling fluids with different viscosities were investigated for different pipe diameters, and ultrasonic echo signals in drilling fluids were obtained. Finally, it is found that there are obvious correlations be-tween drilling fluid viscosity and four key parameters: temperature, pipe diam-eter, ultrasonic echo signal amplitude and ultrasonic attenuation coefficient. The experimental results show that the viscosity detection of drilling fluid can be realized by using the ultrasonic attenuation detection technique, and the ul-trasonic signals are analyzed using the support vector regression machine, which realizes accurate prediction of drilling fluid viscosity. It provides a new idea for drilling fluid viscosity detection.

Keywords

Ultrasound; Drilling Fluid; Viscosity; Attenuation

1. Introduction

Drilling is a crucial step in oil exploration and extraction, and its safety is of utmost importance for ensuring the stability and security of production operations. In the past, serious accidents such as lost circulation, well kicks, and even blowouts frequently occurred at drilling sites, posing a great threat to personnel safety and environmental protection, which highlights the urgent need for drilling safety (Ying-jie ZHOU, 2008). In oil and gas drilling engineering, the main functions of drilling fluid include transporting cuttings to the surface, preventing blowout problems, and providing cooling and lubrication for the drill pipe. The viscosity of drilling fluid is a key parameter for evaluating the quality of drilling fluid. An appropriate viscosity can ensure that the drilling fluid effectively carries the cuttings and waste generated during the drilling process, preventing them from clogging the wellbore and keeping the wellbore clear. Therefore, real - time monitoring of the viscosity of drilling fluid during the drilling process is crucial, and timely adjustment of drilling parameters is necessary to ensure the safety and efficiency of drilling operations.

Commonly used methods for detecting the viscosity of drilling fluid mainly include the capillary method, the rotational method, the falling - body method, etc(W. P. Mason and H. J. McSkimin,1949). Traditional measurement methods are widely used in viscosity evaluation, but these methods require collecting drilling fluid samples, which are cumbersome to operate and cannot perform real - time monitoring. In contrast, ultrasonic detection has the advantages of non - contact measurement, real - time monitoring, and high precision, which can avoid the limitations of traditional methods and safely and reliably monitor the viscosity of drilling fluid. There are many branches of methods for measuring fluid using different principles of ultrasonic technology by domestic and foreign scholars, mainly including ultrasonic Doppler technology, ultrasonic guided wave method, ultrasonic shear wave multiple reflection method, and ultrasonic attenuation method. Thomas G. Hertz et al. used ultrasonic Doppler technology to emit ultrasonic waves with a frequency of 10.4 MHz in a glycerol - water mixture of a mixed closed fluid and measured the induced flow velocity(Hertz, T.G.; Dymling, S.O.; Lindstrom, K.; Persson, H.W.,1991). By changing the temperature to adjust the shear viscosity, they proved that there is an inverse relationship between the induced flow velocity and the shear viscosity. Guo Min et al. emitted ultrasonic waves with a frequency of 3 MHz and collected the ultrasonic Doppler frequency - shift signals reflected by a small ball during its falling process in a 20℃ glaze slurry. The viscosity obtained was almost the same as that measured by a rotational viscometer. Yin Bangtang et al. established an experimental platform for gas kick detection based on Doppler ultrasound based on the gas - liquid multiphase flow theory(Bangtang YIN et al.,2020), and conducted time - domain and frequency - domain analyses on the signals of Doppler ultrasound after propagating in a gas - water two - phase flow (sucrose solution). It showed that as the viscosity increased, the amplitude and variation of the Doppler ultrasonic signal voltage in the solution decreased. Prasad et al. used ultrasonic guided waves to propagate in a refractory buffer rod.(Prasad, V.S.K. et al,2008) The ultrasonic waves were transmitted to the melt through the vibration of a piezoelectric transducer, and the viscosity and temperature of three different glass samples were measured at high temperatures. The measurement results were consistent with the viscosity values provided by the National Institute of Standards and Technology of the United States.

Since fluid viscosity is one of the factors affecting ultrasonic attenuation, many domestic and foreign scholars have carried out research on measuring viscosity using ultrasonic attenuation in fluids. Yang Jinhai theoretically deduced the relationship between the viscous absorption attenuation of ultrasonic waves in fluids and fluid viscosity, proving the possibility of measuring fluid viscosity by the ultrasonic attenuation method. Laux et al. emitted ultrasonic waves with a frequency of 25 MHz to propagate in mango juice(Didier Laux et al,2013). By using the measured propagation velocity and acoustic attenuation, they obtained the longitudinal viscosity of mango juice, which was close to the result measured by a rotational viscometer, verifying the effectiveness of the ultrasonic attenuation method in measuring longitudinal viscosity.

In this paper, the ultrasonic attenuation detection method will be adopted to design an experimental device for detecting the viscosity of drilling fluid using ultrasound, build an experimental platform for detecting the viscosity of drilling fluid using ultrasound, analyze the influence rules of ultrasonic wave propagation in drilling fluid under different pipe diameters and viscosities in combination with the characteristics of the echo signals of ultrasonic wave propagation, and finally verify the accuracy and effectiveness of the ultrasonic transmission method for detecting the viscosity of drilling fluid.

2.Ultrasonic attenuation analysis and transmission detection method

2.1. Analysis of ultrasonic wave equation and attenuation characteristics

Due to the advantages of carrying the basic information of the medium and the characteristics of non - invasiveness, non - contact, and low cost (Yuqin Wang. et al,2024), ultrasonic waves are widely used in fluid detection. Ultrasonic detection technology mainly measures three parameters of ultrasonic waves in drilling fluid: sound velocity, sound attenuation, and acoustic impedance. Thus, it can be divided into the ultrasonic sound velocity detection method, the ultrasonic attenuation detection method, and the acoustic impedance detection method. This paper mainly adopts the ultrasonic attenuation detection method. When ultrasonic waves propagate in drilling fluid, they will cause the compression or expansion of the drilling fluid(V. Narasimhan, R. T. Beyer,2005). According to the law of conservation of mass, the difference between the mass flowing into a volume element and the mass flowing out of it per unit time is the change in mass within this volume element. From this, the continuity equation of sound waves can be obtained:

$$-\frac{\partial}{\partial x}(\rho V)=\frac{\partial p}{\partial t} \tag{1-1}$$

In the formula: V represents the volume of the drilling fluid; ρV represents the flow density of the drilling fluid.

Therefore, by simplifying the equation of motion, the continuity equation, and the equation of state, the wave equation for sound pressure in the ideal drilling fluid is obtained as follows:

$$\frac{\partial^2 p}{\partial t^2} = c^2 \frac{\partial^2 p}{\partial x^2} \tag{1-2}$$

Substituting the velocity of the particle, the wave equation for the displacement of the particle can be obtained.

$$\frac{\partial^2 \xi}{\partial \mathrm{t}^2} = c^2 \frac{\partial^2 \xi}{\partial \mathrm{x}^2} \tag{1-3}$$

In the formula, ξ represents the displacement of the drilling - fluid particle.

Drilling fluid can be regarded as an elastic medium composed of many closely - connected particles. When these particles are disturbed, they will deviate from their equilibrium positions and cause relative changes in volume. From the adiabatic bulk modulus of the drilling fluid, the following can be obtained:

$$dP = -K_S \frac{dV}{V} = -K_S \Delta \tag{1-4}$$

In the formula, K_S is the bulk modulus; Δ is the relative volume change.

Based on the above equation, the sound pressure can be expressed as the following formula.

$$p = -K_S \frac{\partial \xi}{\partial x} \tag{1-5}$$

In acoustic theory, the change in sound pressure is equal to the negative of the viscous force. Therefore, the increment of sound pressure can be expressed as the following formula.

$$p = -T' = \eta \frac{\partial v}{\partial x} \tag{1-6}$$

By simplifying the above equations, the wave equation related to the displacement ξ of ultrasonic waves propagating in the drilling fluid can be obtained as the following formula.

$$\rho \frac{\partial^2 \xi}{\partial t^2} = K_s \frac{\partial^2 \xi}{\partial x^2} + \eta \frac{\partial^3 \xi}{\partial x^2 \partial t} \tag{1-7}$$

It can be seen from the derived wave equation of ultrasonic wave propagation in drilling fluid that this equation is closely related to the viscosity of the drilling fluid, which reflects the influence of viscosity on the propagation of ultrasonic waves in the drilling fluid.

When ultrasonic waves propagate in drilling fluids, the degree of acoustic attenuation depends not only on the frequency, but also on the rheological properties of the drilling fluid. The attenuation of ultrasonic waves in drilling fluids can be classified into three types, namely, diffusion attenuation, scattering attenuation, and absorption attenuation, depending on the principles that cause the attenuation of ultrasonic waves. The scattering attenuation and absorption attenuation of ultrasonic wave follow the exponential law, when a beam of plane wave propagates a certain distance in the drilling fluid, the return wave amplitude and the propagation distance have the following equation(C J Pethick et al., 1987).

$$\alpha = -\frac{1}{d}\ln\left(\frac{A}{A_0}\right) \tag{1-8}$$

where A_0 is the initial ultrasonic amplitude; α is the acoustic attenuation coefficient; d is the propagation distance.

When the diameter of the particles in the fluid is much smaller than the wavelength of the ultrasonic waves, the attenuation caused by scattering is negligible; if the scattering attenuation is not taken into account, but only viscous attenuation and thermal conduction attenuation, there is the classical Stokes-Kirchhoff (George Gabriel Stokes,1845) formula for acoustic attenuation:

$$\beta = \alpha_s + \alpha_a = \frac{\omega^2}{2\rho_0 c^3}\left[\frac{4}{3}\eta' + \chi\left(\frac{1}{C_r} - \frac{1}{C_P}\right)\right] \tag{1-9}$$

Where β is the attenuation coefficient of ultrasonic waves. The formula consists of the sum of viscous absorption and thermal conduction absorption, which indicates that ultrasonic attenuation is related to density, speed of sound, viscosity, temperature and that the attenuation coefficient is directly related to fluid viscosity. Therefore, the viscosity of drilling fluid can be measured indirectly by measuring the attenuation value of ultrasonic waves.

2.2. ultrasonic transmittance

The basic principle of using ultrasonic attenuation method to measure the viscosity of drilling fluid is the propagation of ultrasound in drilling fluid and the information related to the viscosity of drilling fluid contained in the ultrasonic echo signal, and then the viscosity value of drilling fluid can be predicted by analysing the received ultrasonic echo signal. The application of ultrasonic waves in drilling fluids generally utilises ultrasonic transducers for ultrasonic wave transmission and reception. And the ultrasonic detection method can be divided into transmission type and pulse reflection type according to the difference of the echo signal it receives. Compared with the pulse reflection detection type, although the pulse transmission type requires the use of two ultrasonic transducers, it can effectively avoid the coupling of the transmitted signal with the echo signal because the transmission and reception processes do not interfere with each other. Therefore, transmission detection is more suitable for drilling fluid viscosity testing. Ultrasonic transmission detection of drilling fluids is carried out by two ultrasonic transducers, one transmitting and one receiving. The two transducers are located on both sides of the drilling fluid to be inspected and their centre axes coincide and are perpendicular to the upper and lower surfaces of the workpiece. A schematic diagram of the ultrasonic transmission detection type is shown in Figure 1.

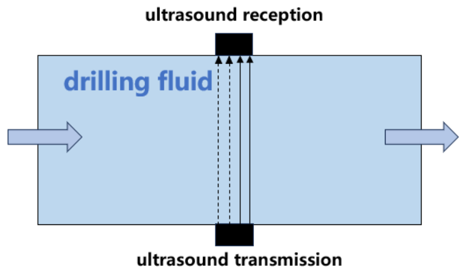


Fig.1 Ultrasonic Transmission Inspection Chart

3. Drilling fluid viscosity testing experiment

In practice, the attenuation of the ultrasonic echo signal is affected by a variety of factors, which increases the difficulty of drilling fluid viscosity detection. Therefore, according to the basic principle and detection mode of ultrasonic detection, this paper carries out the design of the experimental device for drilling fluid viscosity detection in order to explore the change characteristics of the attenuation of ultrasonic waves when they propagate in drilling fluids and accurately predict the viscosity of drilling fluids through algorithms. The aim is to explore the propagation and attenuation of ultrasonic waves in drilling fluids of different temperatures and viscosities, and detailed experimental tests were carried out on different pipe diameters. Drilling fluid viscosity testing experiment.

3.1. Experimental platform design for drilling fluid viscosity testing experiments

The block diagram of the ultrasonic drilling fluid viscosity detection system constructed in this paper is shown in Fig. 2. The principle of the ultrasonic attenuation viscosity detection system is as follows: the ultrasonic excitation signal is output from the signal generator, and then amplified by the power amplifier; the ultrasonic transmitting transducer receives the amplified signal, and then converts it into acoustic signals and transmits it into drilling fluid by inverse piezoelectric effect; after transmitting the ultrasonic signal through the drilling fluid, it is received by the ultrasonic receiving transducer, and then converts it into electrical signals by positive piezoelectric effect; the digital oscilloscope continuously collects the ultrasonic receiving transducer and converts it into electrical signals. The ultrasonic signal is transmitted through the drilling fluid and then received by the ultrasonic receiver transducer, which converts the received ultrasonic signal into an electrical signal under the action of positive piezoelectric effect; the amplitude signal of the ultrasonic receiver transducer is continuously collected by the digital oscilloscope, and then stored and uploaded to the computer to analyse the data. Drilling fluid viscosity testing experiment.

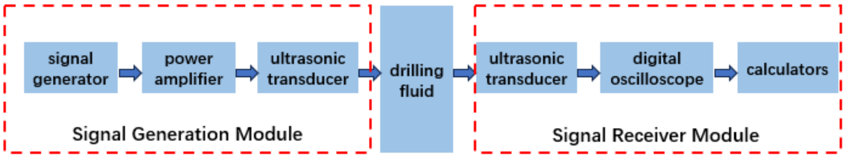


Fig.2 Block diagram of ultrasonic drilling fluid viscosity testing system

The experimental setup for ultrasonic drilling fluid viscosity detection is shown in Fig. 3. The main equipment used in the experiment are signal generator, power amplifier, PVC pipe, ultrasonic generator transducer, receiver transducer and oscilloscope, as well as the drilling fluid to be detected.

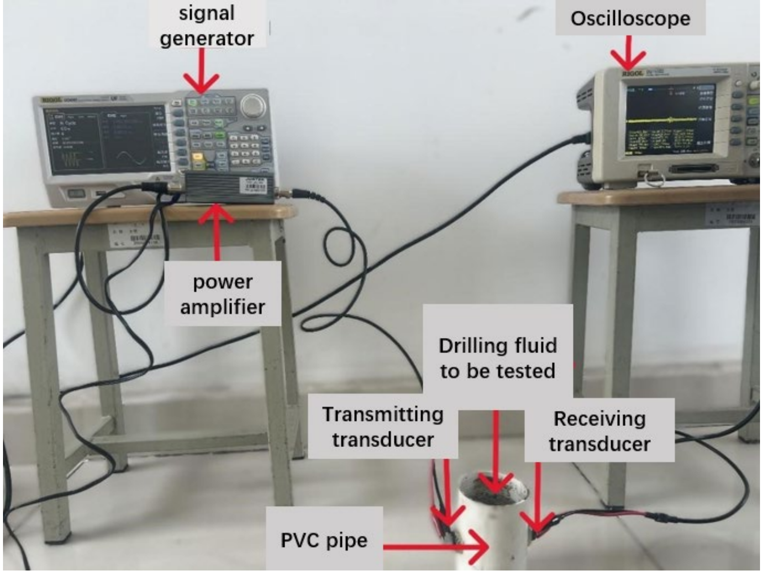


Fig.3 Ultrasonic drilling fluid viscosity testing experimental platform

3.2. Experimental programme and steps

In this paper, the viscosity of drilling fluid at different temperatures is measured using NDJ-1 rotational viscometer, which has a measuring range of 10mPa-s~100000mPa-s and a measuring error of ±5%. This viscometer is widely used to measure the viscosity of various fluids such as paints, plastics, adhesives, etc. Therefore, the experiments in this paper will take the viscosity value of drilling fluid at different temperatures measured by NDJ-1 rotational viscometer as the viscosity standard. viscosity values as the viscosity standard. Its material is shown in Fig. 4, and the range table is shown in Table 1.

(a) NDJ-1 Rotational Viscometer (b) Rotor No. 2

Fig.4 NDJ-1 rotational viscometer physical picture

Table 1. Rotational Viscometer Range Table (Unit: mPa-s)

rotors	Speed 60r/min	Speed 30r/min	Speed 12r/min	Speed 6r/min
0	10	20	50	100
1	100	200	500	1000
2	500	1000	2500	5000
3	2000	4000	10000	20000
4	10000	20000	50000	100000

The amplitude of ultrasonic attenuation signals under different drilling fluid viscosities of 20℃, 25℃, 30℃, 35℃ and 40℃ were collected through experiments and carried out in PVC pipes with pipe diameters of 32mm, 50mm and 75mm, respectively, and 20 sets of experimental sample data were collected under each temperature, and a total of 300 sets of experimental data were collected. The detailed operation steps of the whole experimental testing are as follows:

(1) Ultrasonic transducer installation. Install two ultrasonic transceivers with a frequency of 40 kHz at both ends of the PVC pipe to be tested. Use hot melt glue to fix the transducers to ensure that the transmitting transducer and receiving transducer are located on the same level.

(2) Detection device connection. Connect the signal generator to the power amplifier, and then connect the output of the power amplifier to the transmitting end of the ultrasonic transducer. Connect the oscilloscope to the receiving end of the ultrasonic transducer.

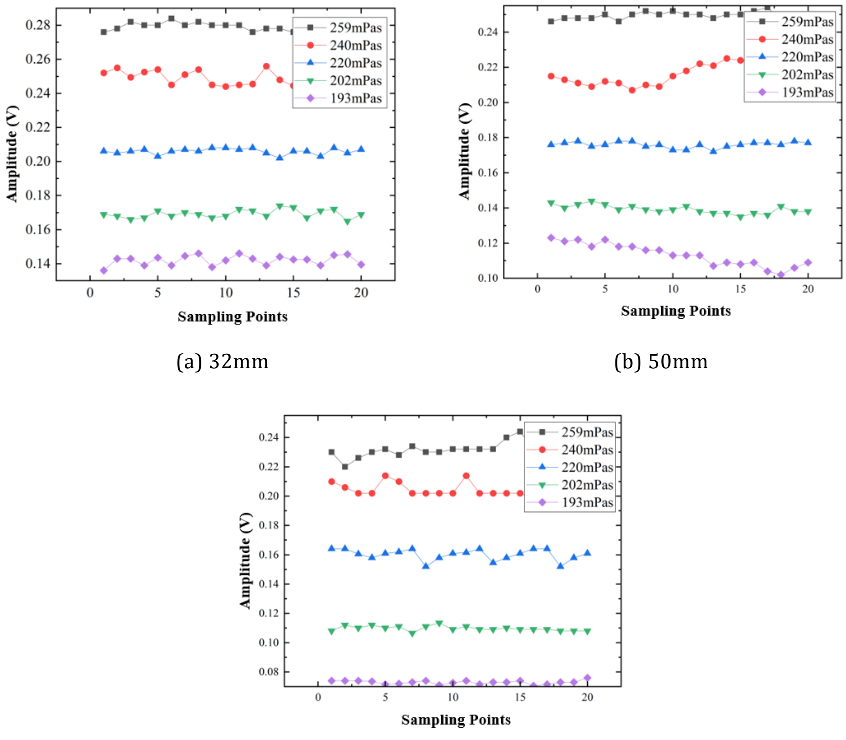
(3) Wiring check. Check whether the connection of the detection device is correct, make sure that the circuit is connected correctly, and then switch on the power supply.

(4) Ultrasonic excitation signal setting. Use the signal generator to set a 40kHz, amplitude 20V, cycle number 4, period 10ms pulse burst signal as the experimental ultrasonic excitation signal. The signal amplitude was increased to 40V by a power amplifier with an amplification of 2.

(5) Drilling fluid loading. The heated drilling fluid to be tested was stirred thoroughly and then poured into the PVC pipe.
(6) Data Acquisition. Use an oscilloscope to detect the acoustic pressure amplitude of the receiving transducer and save the waveform data after the correct waveform is observed.
To avoid the influence of drilling fluid settling on the experimental results, steps (5) and (6) should be repeated before each data collection. Repeat steps (1) to (6) when measuring drilling fluid at different temperatures and when performing measurements at different pipe diameters.

3.3. Analysis of experimental results

By changing the temperature to change the viscosity of the drilling fluid, the amplitude of ultrasonic echo signals were measured at different viscosities in a PVC pipe with a diameter of 32 mm in Fig. 5(a), in a PVC pipe with a diameter of 50 mm in Fig. 5(b), and in a PVC pipe with a diameter of 75 mm in Fig. 5(c).



(a) 32mm

(b) 50mm

(c) 75mm

Fig.5 Amplitude of ultrasonic echo signals of drilling fluids in different pipe diameters

The relationship between the viscosity of drilling fluid and the amplitude of ultrasonic echo signal in different pipe diameters can be seen in Figure 5. When the viscosity of drilling fluid is unchanged, the amplitude of ultrasonic echo signal of drilling fluid is relatively stable without significant decrease or fluctuation, although there are some fluctuations. The ultrasonic echo signal amplitudes of different viscosities have obvious differences. As the temperature increases, the viscosity of the drilling fluid decreases, and the amplitude of the ultrasonic echo signal also decreases. With the increase of pipe diameter, the amplitude of ultrasonic echo signal decreases in all the same viscosity conditions, which is in line with the expectation that the amplitude of ultrasonic wave decreases when it propagates over a longer distance.

The average amplitude of ultrasonic echo was calculated from 20 sampling points with different viscosities at different temperatures in 32mm, 50mm and 75mm pipe diameters, and the acoustic attenuation coefficients of different drilling fluid viscosities were calculated by the equation of echo amplitude and propagation distance 1-8 with the initial ultrasonic amplitude of 40V, to investigate the relationship between viscosity, pipe diameter and ultrasonic attenuation coefficients. The acoustic attenuation coefficients under different pipe diameters and viscosities are shown in Table 2, and the relationship between different pipe diameters, viscosities and acoustic attenuation is shown in Fig. 6.

Table 2. Sound attenuation coefficients for different pipe diameters and viscosities

Pipe diameter (mm)	Temperature (°C)	Viscosity(mPa-s)	Echo amplitude (V)	Attenuation factor (Np/m)
32	20	259	0.280	155.11
32	25	240	0.249	158.72
32	30	220	0.206	164.65
32	35	202	0.170	170.74
32	40	193	0.132	178.56
50	20	259	0.250	101.54
50	25	240	0.217	104.33
50	30	220	0.176	108.52
50	35	202	0.140	113.17
50	40	193	0.114	117.30
75	20	259	0.234	67.70
75	25	240	0.206	69.56
75	30	220	0.160	72.35
75	35	202	0.110	75.45
75	40	193	0.073	78.20

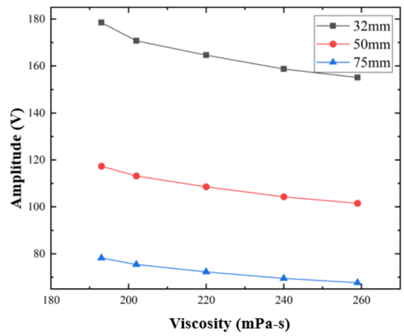


Fig.6 Relationship between viscosity and ultrasonic attenuation at different pipe diameters

As can be seen from Table 2 and Figure 6, for all pipe diameters, the ultrasonic attenuation coefficient decreases as the viscosity increases from 193 mPa-s to 259 mPa-s. For the same viscosity, the attenuation coefficient decreases as the tube diameter increases. For example, the highest attenuation coefficient is 155.11 Np/m for 32 mm pipe diameter and the lowest is 67.70 Np/m for 75 mm pipe diameter for a viscosity of 259 mPa-s. This shows that the larger pipe diameter allows ultrasonic waves to propagate with a lower attenuation coefficient. And it can be seen that the attenuation coefficients of different pipe diameters have similar trends with viscosity, but there is a significant difference in the values, which may be due to the fact that ultrasonic waves propagate in different diameters of the pipe under the influence of different boundary effects, in the smaller diameter of the pipe, ultrasonic waves interact with the pipe wall more, and the attenuation coefficient increases, when the diameter of the pipe increases, ultrasonic waves interact with the wall less and the attenuation coefficient When the pipe diameter increases, the interaction between ultrasonic waves and pipe wall decreases, and the attenuation coefficient decreases.

In summary, different viscosities and pipe diameters have an important influence on the ultrasonic echo amplitude and ultrasonic attenuation coefficient. With the change of temperature, the viscosity of drilling fluid changes, and accordingly, the amplitude of ultrasonic echo signal also changes, showing an inverse relationship between the amplitude and viscosity. Similarly, the change of ultrasonic attenuation coefficient reflects the change of viscosity, i.e., the attenuation coefficient decreases with the increase of viscosity. In addition, the effect of pipe diameter on the ultrasonic signal should not be ignored. The amplitude and attenuation coefficient of the ultrasonic echo signals under different pipe diameters show a consistent trend, pointing out the significant influence of pipe diameter on the propagation characteristics of ultrasonic waves. In the larger pipe diameter, the ultrasonic echo signal amplitude decreases, and the attenuation coefficient also decreases, which shows that the energy loss of ultrasonic propagation is positively related to the pipe diameter. Therefore, it can be concluded that the four variables of temperature, ultrasonic echo signal amplitude, ultrasonic attenuation coefficient and pipe diameter are interrelated and can reflect the changes in the viscosity of drilling fluids, and they can be effectively used as characteristic quantities of ultrasonic drilling fluid viscosity detection to monitor and judge the changes in the viscosity of drilling fluids.

4. Prediction of drilling fluid viscosity based on support vector regression machine

When using ultrasonic testing of drilling fluid viscosity, the characteristic quantity of ultrasonic sound attenuation signal can reflect the information of drilling fluid viscosity, indicating the change of drilling fluid viscosity, and the characteristics of ultrasonic attenuation signal can be analysed to indirectly obtain the information of drilling fluid viscosity. In the actual inspection of drilling fluid, the ultrasonic detection signal will be affected by a variety of factors, and it is not possible to directly and accurately derive the viscosity of drilling fluid through the ultrasonic attenuation signal. In order to overcome this problem, this chapter introduces the support vector regression machine into the ultrasonic drilling fluid viscosity prediction, and establishes the ultrasonic attenuation signal drilling fluid viscosity prediction method based on the support vector regression machine. When ultrasonic waves are used to detect drilling fluid viscosity in practice, the ultrasonic attenuation signal data samples are often limited and scattered. The support vector regression machine is a machine learning algorithm for small samples based on statistical learning theory, which can achieve higher accuracy and generalisation for the identification and analysis of small samples.

4.1. Support Vector Regression Machine Algorithm Fundamentals

The core idea of SVR method is to map the sample data that is not easy to regress in low-dimensional space to high-dimensional space, and after obtaining the data that is easy to regress, the minimum distance to the optimal hyperplane is achieved by minimising the training samples.SVR is able to take into account the complexity of the model and the learning ability, and has obvious advantages in solving the problem of small samples, nonlinear and high-dimensional pattern recognition. The support vector machine regression machine modelling solution process is:

Define a collection of training sample data:

$$X = \{(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\} \tag{4-1}$$

where $x_i \in R^n$ is the input parameter of the first sample, i.e., the input feature; $y_i \in R$ is the corresponding output label, i.e., the predicted value.

For the nonlinear SVR problem of measuring drilling fluid viscosity by ultrasonic attenuation, a linear regression model can be built in the high-dimensional feature space by mapping the input data into the high-dimensional space through the nonlinear function , :

$$f(x) = w \cdot \varphi(x) + b \tag{4-2}$$

At this point the SVR objective function can be expressed as:

$$\begin{cases} \min \ \dfrac{1}{2}\| w\|^2 + c\sum_{i=1}^{l}\left(\xi_i + \xi_i^*\right) \\ s.t. \ \ f(x_i) - y_i \le \varepsilon + \xi_i \\ \qquad y_i - f\left(x_i\right) \le \varepsilon + \xi_i^* \\ \qquad \xi_i \ge 0, \xi_i^* \ge 0, i = 1, 2, \ldots, l \end{cases} \tag{4-3}$$

where , c is the penalty function; ε is the model insensitive loss parameter; ξ_i is the slack variable, indicating the degree of sample deviation from the insensitive region.

Considering the nonlinearity of ultrasonic attenuation measurement of drilling fluid viscosity, combined with the advantages of RBF kernel function with good state and wide application, this paper adopts the RBF kernel function as the kernel function of SVR, at this time, the regression function expression is:

$$f\left(x\right) = \sum_{i=1}^{n}\left(\alpha_i - \alpha_i^*\right)\exp\left\{-\frac{\left\|x_i - x_j\right\|^2}{2g^2}\right\} + b \tag{4-4}$$

4.2. Indicators for the evaluation of predictive models

Based on the ultrasonic drilling fluid viscosity prediction results, this chapter introduces three evaluation metrics to assess the machine learning regression model: mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R2). MAE is the mean of absolute error, which can intuitively reflect the prediction performance; RMSE can reflect the size of the error; and R2 illustrates the goodness of fit of the established prediction model to the real data. R2 indicates the fit between the established prediction model and the real data, and its value is close to 1, the more accurate the prediction model is. Assuming that the real value is $y = \{y_1, y_2, \ldots, y_n\}$ and the predicted value is $y^* = \{y_1^*, y_2^*, \ldots, y_n^*\}$, the formulas of the three evaluation indexes are shown in Equation (4-5) to Equation (4-7).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - y_i^*\right| \tag{4-5}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - y_i^*)^2} \tag{4-6}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(y_i - y_i^*\right)^2}{\sum_{i=1}^{n}\left(y_i - \overline{y}_i\right)^2} \tag{4-7}$$

4.3. SVR-based drilling fluid viscosity prediction

According to the ultrasonic drilling fluid viscosity detection experiments, the ultrasonic echo amplitude signals of drilling fluids with different temperatures and viscosities as well as different pipe diameters were obtained, with a total of 300 sets of ultrasonic signal data feature samples, and the four variables that can reflect changes in the viscosity of drilling fluids, namely, temperature, ultrasonic echo amplitude, ultrasonic attenuation coefficient and pipe diameter, were taken as input feature quantities of the support vector regression machine. The sample data set was divided into training set and test set according to the ratio of 8:2, and then the samples inside the training set and test set were randomly disrupted to predict the viscosity of drilling fluid using the support vector regression machine model.The prediction results of the training set and the test set of the SVR model are shown in Fig. 7 and Fig. 8, respectively.

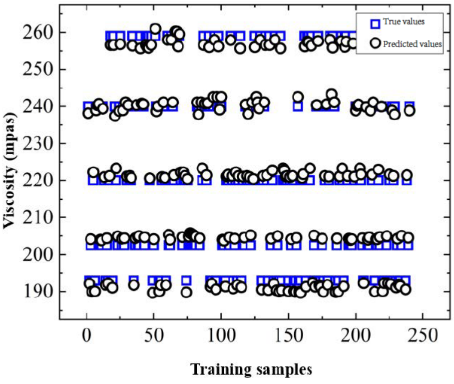


Fig.7 SVR training set prediction results s

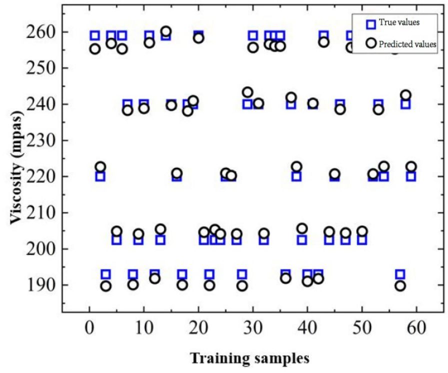


Fig.8 SVR test set prediction results

According to the prediction model evaluation index, the mean absolute error (MAE) of the training set and test set of the SVR prediction model are 1.7829 and 2.1272, the root mean square error (RMSE) is 1.9707 and 2.3369, and the coefficients of determination (R2) are 0.9761 and 0.9915, respectively, as shown in Table 3, which shows that the SVR method has a good effect on the prediction of the viscosity of drilling fluid. prediction of drilling fluid viscosity.

Table 3. The key parameters of each solid model in the simulation model

SVR	MAE	RMSE	parameter declaration
Training set	1.7829	1.9707	0.9761
Test set	2.1272	2.3369	0.9915

5. Conclusion

In this paper, a drilling fluid viscosity detection method based on the ultrasonic attenuation method is proposed, which is verified through experiments on drilling fluids at different temperatures. Through the experimental analysis of ultrasonic transmission method, it is obtained that with the change of temperature, the viscosity of drilling fluid changes, and the amplitude of ultrasonic echo signal also changes, showing that the echo amplitude is inversely proportional to the viscosity. In addition, the larger the pipe diameter is, the ultrasonic echo signal amplitude decreases, and the attenuation coefficient also decreases. Therefore, the viscosity of drilling fluid can be reflected by detecting the echo amplitude after ultrasonic wave propagation in the drilling fluid. The four variables of drilling fluid temperature, ultrasonic echo signal amplitude, ultrasonic attenuation coefficient and pipe diameter can be effectively used as characteristic quantities of ultrasonic viscosity detection of drilling fluid, which can be used to monitor and judge the viscosity value of drilling fluid. The experiments in this paper can be further improved, such as combining different factors of drilling fluid and adding more different drilling fluid viscosity quantities for model training, so that the drilling fluid viscosity prediction can be more effective.

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