Experimental study on the choice of transducer resonance frequency in downhole flow measurement

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Abstract. In the process of downhole layered oil recovery, it is necessary to measure the liquid production of each layer in real time, so as to control the oil production plan of each layer in real time according to the oil production plan. Need to use ultrasonic time difference flowmeter to measure the flow in the process of injection and production. Due to the complex and changeable downhole environment, impurities such as sand and bubbles often appear in the process of downhole flow measurement. How to choose a suitable ultrasonic transducer frequency is of great significance to the flow measurement results. At present, common transducer resonance frequencies on the market mainly include 1MHz, 500KHz, 180KHz, and 40KHz. In this paper, the attenuation characteristics of the resonant signal of the transducer in the medium containing impurities are studied through simulation and experiment. The experimental data shows that in the stratified oil recovery system, the receiving effect of the system is best when the transducer frequency is 1MHz.

1. Introduction

Ultrasonic time difference flowmeter is suitable for flow measurement in downhole stratified oil production system because of its accurate measurement, non-contact and strong anti-interference characteristics. The installation effect of the transducer, the flow characteristics of the fluid medium and the attenuation at different frequencies are affected by the ultrasonic time difference flowmeter measurement signal strength[1-4]. The attenuation of ultrasound refers to the attenuation of the amplitude when propagating in the acoustic medium. This attenuation is not only related to the propagation distance but also to the frequency of the ultrasound. Dingguo Xiao et al. proved through experiments
that the higher the sound wave frequency, the faster the attenuation rate\cite{5-6}. When ultrasonic flowmeter is used for downhole measurement, the medium often contains impurities such as sand and bubbles. Sound waves will reflect and refract after encountering impurities and bubbles during transmission\cite{7}. In 2010, the Yellow River Hydraulic Research Institute conducted an experimental measurement of the speed of sound waves in a water mixture\cite{8}.

The above research mainly focuses on the attenuation of sound waves in a single liquid or the relationship between sound velocity and attenuation in a mixed medium. The research object is relatively single, and there is no research on the attenuation of the sound waves containing impurities in the fluid medium of the stratified oil recovery system. This paper analyzes the attenuation of ultrasonic waves emitted by transducers with different resonance frequencies after passing through the medium, and obtains the best transmitting and receiving frequency in the liquid medium containing impurities. Studying the attenuation characteristics of ultrasonic wave after passing through the medium containing impurities is of great significance to the accuracy improvement of ultrasonic flowmeter.

2. The principle of downhole flow measurement

As shown in Fig. 1, when there is no liquid in the pipeline or the flow rate of the liquid in the pipeline is zero, the time from the sound wave from transducer A to transducer B is the same as the time from transducer B to transducer A. When there is liquid with v in the pipeline, the time from the sound wave from transducer A to transducer B will be less than the time from transducer B to transducer A. The time difference in the time difference method is this time difference. In practical applications, because the pipe diameter to be measured is known, the speed of sound waves in the liquid to be measured is also known. The angle between the sensor and the pipe installation is also known. Therefore, the main factors affecting the accuracy of flow measurement are the received time difference and the strength of the received signal. Therefore, studying the influence of receiving time and received signal strength on flow measurement is of great significance for improving the accuracy of flow measurement. The receiving time is mainly affected by impurities such as sand and bubbles in the pipeline, the received signal strength and the transmitted power, and the transceiver frequency of the transducer\cite{9}.

![Figure 1 Schematic diagram of time difference method measurement](image)

3. Analysis of the attenuation of the resonance signal of the transducer

3.1. The attenuation theory of transducer resonance signal

The transducer in the ultrasonic time difference flowmeter converts electrical signals into ultrasonic signals. Ultrasound mainly refers to sound waves with a frequency higher than 20KHz. Ultrasound has good directivity, its energy is also very high, it has strong penetrating ability, and it will be reflected and refracted in the process of propagation. Ultrasonic waves will also be attenuated during propagation. The main causes of ultrasonic attenuation are beam attenuation, crystal attenuation and medium attenuation. Ultrasonic attenuation forms mainly include diffusion attenuation, scattering attenuation and absorption attenuation\cite{10}.

Diffusion attenuation refers to the phenomenon that the ultrasonic energy at a certain point changes with distance due to the spread of the waveform when ultrasonic waves propagate in the medium, which is called diffusion attenuation. Scattering attenuation refers to the loss of ultrasonic energy caused by
scattering when ultrasonic waves propagate in media and encounter media interfaces with different acoustic impedances. Absorption attenuation refers to the loss of ultrasonic energy caused by internal friction and heat conduction caused by the vibration of the particles in the medium when ultrasonic waves propagate in the medium. For liquid media, the attenuation is mainly caused by absorption attenuation, and the expression of its attenuation coefficient is shown in equation (1).

\[
\alpha = \alpha_n = \frac{8\pi^2 f^2 \eta}{2\rho c^3}
\]

Equation (1) is the attenuation coefficient, and the larger its value, the more severe the attenuation. Is the frequency of ultrasound; is the viscosity of the medium; is the density of the medium; is the wave speed. From the expression of the attenuation coefficient, it can be concluded that the attenuation of the sound wave is related to the density and velocity characteristics of the medium and also related to the frequency of the ultrasonic wave[11].

From equation (1), it can be concluded that when the physical characteristic density of the medium and the speed in the medium are determined, the relationship between the attenuation of the ultrasonic wave and the frequency \( f \) is that the higher the frequency, the stronger the attenuation of the ultrasonic wave in the medium.

When ultrasonic waves propagate in a medium containing impurities, because the acoustic impedance of the medium and the impurities are different, scattering attenuation occurs at this time. Especially when the impurity grains are large, the sound wave will be refracted and reflected, which will affect the reception of the transducer. At the same time, because the medium contains impurities such as bubbles, the ultrasonic wave will be diffracted during the propagation process, which increases the attenuation of the ultrasonic wave during the propagation process.

3.2. Simulation analysis of the relationship between the attenuation of the transducer resonance signal and the frequency

Experiment with the frequency of sensors commonly used in the market through simulation, and select the maximum amplitude of the signal received by the transducer after passing through the pipeline. Therefore, 1MHz, 500KHz, 180KHz, and 40KHz are selected in the simulation to compare the received amplitude of these frequencies.

As shown in Fig. 2, this model is a model that simulates the case of sand and bubble impurities in the downhole stratified oil recovery system. The transducer emits pulses with the same amplitude as the pipeline, and is received by the transducer again after passing through the fluid medium containing impurities. The waveform curve received by the transducer is shown in Fig. 3.
Figure 3. Transducer receiving waveforms at different resonance frequencies

The abscissa of Fig. 3, represents the time for the transducer to transmit and receive, and the ordinate represents the amplitude of the pulse wave. The signal amplitude at the receiving end is amplified 50 times. Combining the simulation results of Fig. 2 and Fig. 3, it can be seen that under the condition that there are some impurities in the same transmitting amplitude pipeline, the transducer has the largest receiving amplitude at a frequency of 1 MHz. The receiving amplitude of 500KHz and 180KHz transducers decreases in turn, and the receiving amplitude of 40KHz increases compared with that of 500KHz and 180KHz. The transmitter and receiver signals of the transducer are simulated under different impurity concentrations, the transducer is simulated under the condition of different impurity diameters, and the receiving amplitude is compared to obtain a graph as shown in Fig. 4.

Figure 4 The influence of ultrasonic frequency and impurity diameter on the received amplitude

The receiving amplitude of the four frequency transducers participating in the experiment decreases as the diameter of the impurity increases. Although the ultrasonic wave decays faster as its frequency increases, the 1MHz reception value in the experimental data is still much larger than the reception amplitude of other frequencies. The factor causing this situation may be because the higher the frequency of the ultrasonic wave during the launch, the higher its energy. Although it will decay after passing through a small pipe diameter, its energy is still the highest at this time. The receiving waveforms of 500KHz and 180KHz decrease successively, and the waveform of 40KHz increases again. However, the number of 40KHz waveforms per unit time is obviously less and the time period is relatively long. In the actual application process, if the number of waveforms is too small, it is not conducive to signal acquisition and conditioning. At the same time, the longer cycle time makes the reduction of the number of received waveforms per unit time not conducive to the improvement of measurement accuracy.

3.3. Simulation of the relationship between the attenuation of the resonance signal of the transducer and the impurities

From the previous simulation, we already know that when ultrasonic waves pass through a medium containing impurities, the 1MHz transducer receives the largest amplitude. Therefore, we will study the
relationship between the amount of impurities and the waveform attenuation through a frequency of 1MHz. As shown in Fig. 5, the models with different amounts of impurities and the amplitudes received by their transducers are described.

![Graph showing relationship between amount of impurities and receiving amplitude](image)

**Figure 5** Diagrams of different amounts of impurities and the relationship between receiving amplitude attenuation and the number of impurities

It can be seen from the simulated receiving amplitude that the receiving amplitude decreases significantly as the number of impurities increases. The reason for this may be that as the impurities increase, the sound wave will be refracted and reflected during the propagation process. The intensity of the wave that the transducer can receive is affected, and the scattering attenuation will also occur in this process, which affects the received signal\[12\].

4. Experimental verification

Four transducers with different frequencies are installed on the outer pipe wall of the constructed stratified oil production system, and sand impurities with different diameters are added to the pipe to measure the signal received by the transducer. The received amplitude obtained by driving the transducer with the same transmitted amplitude pulse is shown in Fig. 6.

![Graph showing transducer receiving amplitude under different impurity conditions](image)

**Figure 6** Transducer receiving amplitude under different impurity conditions
Through experimental verification, it can be found that the receiving curve is basically in line with the simulation. In the experiment, the difference in the receiving amplitude of the 500KHz and 180KHz transducers is not big, but the receiving amplitude of the 1MHz transducer is still the largest. The water used in the experiment is tap water, and there will be some bubbles in the tap water because of the disinfectant water. The diameter of these bubbles is generally very small, and the impurities in the system are mainly sand, and its diameter is relatively small. Therefore, these impurities and bubbles are extremely easy to diffract with lower frequency waveforms. Through simulation and experiment, it can be concluded that 1MHz frequency transducer is the first choice for the sensor in the stratified oil recovery system.

Second, we need to verify the influence of the amount of impurities on the signal received by the transducer. Take a certain amount of sand with a diameter of about 1mm to conduct an experiment to measure the influence of the amount of impurities on the signal received by the transducer. The amplitude of the signal received by the transducer obtained through the experiment is shown in Fig. 7.

![Figure 7 The influence of different amounts of impurities on the received signal strength](image)

It can be seen from the figure that as the number of impurities increases, the intensity of the received signal of the transducer is constantly getting smaller. This also verifies the conclusion in the simulation that the increase in the number of impurities will cause the waveform emitted by the transducer to be reflected and refracted after encountering the impurities, which will result in a smaller signal amplitude at the receiving end of the transducer. Therefore, as the number of impurities increases, the signal received by the transducer becomes smaller.

5. Conclusion
This paper mainly studies the influence of the transducer resonance frequency on the signal attenuation in the downhole stratified oil production system and the influence on the signal-to-noise ratio of the measurement system.

①Experiment with the 1MHz, 500kHz, 180KHz, and 40kHz transducers transmitting pulse signals with the same amplitude, and it is concluded that the signal amplitude at the receiving end is the largest at a frequency of 1MHz. Therefore, the 1MHz frequency transducer should be selected in the stratified oil recovery system.

②When impurities appear in the stratified oil recovery system, the transmission signal of the transducer will significantly affect the strength of the received signal due to the reflection of the impurities during the propagation process.

③Although the resonant frequency of the transducer is attenuated more severely as the frequency increases, in the actual flowmeter, the 1MHz transducer receives better signal strength than the low-frequency transducer.

References
[1] Sheng Liying. Ultrasonic Testing Technology[M]. Beijing: ChemicalIndustry Press, 2014.5.
[2] Wang Luona. Research on downhole flow measurement technology of layered oil production with ultrasonic time difference method[D]. Xi’an Shiyou University, 2020.
[3] Jiawen Yin, Qin Wei, Liyong Zhu et al. Nonlinear frequency mixing of Lamb wave for detecting randomly distributed microcracks in thin plates [J]. Wave Motion, 2020, 99.

[4] Ding-guo Xiao, Zheng Zhang, Yan-ling Zhu, Jia-qi Zhang, Chun-guang Xu, Xin Ma. The Frequency Dependence of Ultrasonic Attenuation in Water [A]. IEEE Beijing Section, 2016:4.

[5] Huang Jiantong, Li Li, Li Changzheng. Study on the characteristics of ultrasonic propagation in muddy water [J]. People's Yellow River, 2010, 32(08):43-44.

[6] Jia Huiqin, Wang Chengyun, Dang Ruirong. The influence of fluid velocity on the accuracy of ultrasonic flow measurement and its calibration [J]. Chinese Journal of Scientific Instrument, 2020, 41(07):1-8.

[7] Qiang Chen, Research on Flow Rate Measurement of Ultrasonic Flowmeter, Shenyang University of Technology [D], 2007

[8] Yuan Yue, Miao Boya, An Yu. Propagation characteristics and heat generation effect of sound waves in bubble-containing liquids [J]. Applied Acoustics, 2018, 37(05):717-721.

[9] Yang Yue. Research on measurement technology of ultrasonic gas flowmeter based on coupling of flow field and sound field [D]. Shandong University, 2020.

[10] Ma Dayou, Shen Hao. Handbook of Acoustics (Revised Edition) [M]. Beijing: Science Press, 2004, 174-175.

[11] Cai Wuchang, Ying Qijia. A new type of flow detection instrument [M]. Beijing: Chemical Industry Press, 2006

[12] Xuefeng Wang, PhD thesis based on the key technology of gas ultrasonic flowmeter based on time difference method, [D] Dalian University of Technology, 2011.