Numerical Simulation Research on Reflected Wave Characteristics of Oil and Gas Well Coupling

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Abstract. In order to analyse and identify the reflection morphology of the coupling reflected wave in the oil jacket annulus and to clarify the influences of different factors on the coupling reflection waveform, the COMSOL finite element analysis software is used to conduct a numerical simulation study on the above situation, and the response characteristics are obtained by calculation. In this paper, different signal sources are used to research the three-dimensional propagation characteristics of acoustic wave when it meets the coupling in the annular space. Numerical simulations are carried out for different coupling thicknesses, different coupling radii, and different oil casing annulus pressures to analyse their influences on the waveform of coupling wave. The results showed that when the polarity of the signal source was positive (negative), the coupling reflection signal was positive (negative) at first and then negative (positive). When the signal source is a positive-negative superimposed source, the first peak polarity of the coupling reflection signal is consistent with the signal source. The reflected signal is superimposed by the response generated by the positive and negative signal sources, respectively. With the increase of the coupling radius, the morphology of coupling wave remains unchanged while its reflected wave amplitude increases nonlinearly with the increase of the coupling radius; with the increase of the oil casing annulus pressure, the morphology of coupling wave does not change, but the amplitude of the reflected wave increases linearly with the increase of the pressure; as the thickness of the coupling increases, the peak-to-peak spacing of the coupling reflection wave becomes larger and the positive and negative peaks separate. The research results can provide theoretical basis and reference standards for the analysis of the characteristics of the signals received by the actual fluid level detector, the performance verification of the echo signal processing method and the correct identification of the dynamic fluid level position.

1. Introduction

In recent years, many scholars have done a lot of research work on the detection of dynamic fluid level in oil wells, but lack of in-depth research on the mechanism of echo generation and its characteristics analysis. Li Xiangyu et al. [1-6] used different methods to establish a hydro-mechanical surface soft-sensing model. However, these are only the research of measurement methods, and there is no in-depth study on the generation mechanism of measurement objects, that is, no systematic research has been made on the characteristics of the echo generated when the acoustic waves propagate in the air of the oil collar. Zhang Peng [7] combined the relevant references and a large amount of field data from oil wells, using mathematical expressions to simulate the coupling signal and the liquid level echo
signal. This is only a simulation of waveform shape, which cannot truly reflect the propagation characteristics of acoustic waves in tube-casing annulus. Liu Yingxin et al. [8] used the pseudorandom code amplitude modulation signal of the cosine carrier as the detection signal to perform oil well echo simulation, and this method of simulating a wideband signal source in the field with a single frequency signal is only a simplified simulation process. Research on the process is still lack of guidance. Zhou Wei et al. [9,10] proposed a method for detecting the fluid level of an oil well based on a string sound field model, and made a lot of analysis on sound field characteristics, but did not study further on the reflection characteristics of acoustic waves which propagate in the string sound field model. Up to now, the related research of acoustic oil wells is mainly for the study of dynamic fluid level measurement methods. There is no systematic research on the reflection mechanism and echo characteristics of acoustic waves in propagating in the air of the oil jacket ring. In addition, most of the methods for estimating the sound velocity and the methods for detecting the dynamic fluid level are directly applied to the actually acquired data to draw conclusions. However, to identify the performance of a method requires a standard as the reference which is the ideal signal in simulation process. In order to be more persuasive, the ideal signal needs to be simulated as close to the actual situation as possible. In view of this, the author uses COMSOL software to build an annulus model of the oil jacket, simulates the reflected waves generated by the coupling under the excitation of different signal sources, conducts a systematic study of the acoustic waves reflection characteristics, and analyses the acoustic waves encountered when propagates in the annulus of the oil jacket. Numerical simulations are carried out for different coupling thicknesses, different coupling radii, and different oil casing annulus pressures to analyse their influences on the waveform of coupling wave. The research results can provide strong support for the popularization and improvement of related theories. The performance verification of the echo processing method provides a correct reference standard, and provides an important theoretical basis for correct identifying the echo position of the dynamic fluid level.

2. Acoustic waves reflection theory of oil and gas wells

The actual oil and gas production well is composed of casing, perforation, tubing with the same length specifications and their couplings, as shown in Figure 1. The acoustic wave generator and the receiver are installed on the ground. The annular space of the oil jacket is formed between the casing and the tubing. There are tubing couplings protruding outwards at the two connected tubing. The tubing couplings will change the width of the oil jacket annulus. The cross-sectional area, the hole on the casing wall is called perforation. The physical structure model of the actual oil and gas production well provides a theoretical basis for the design of the space acoustic wave propagation model of the oil casing ring under ideal conditions. The acoustic wave generator located on the ground generates infrasonic waves propagating down the annulus of the oil jacket. After encountering the coupling, perforation and oil level, a part of the signals will be reflected to produce the corresponding echo signals, and the other part of the infrasonic signals will continue to spread down the annulus of the oil jacket.

![Figure 1. Schematic diagram of oil and gas well level measurement](image)

When the acoustic wave passes through the coupling with changed cross-section, the formula about different acoustic wave parameters can be used to describe the sound pressure reflection coefficient [11].
In formula (1), \( S_1 \) is the cross-sectional area of the upper surface of the coupling and \( S_2 \) is the cross-sectional area of the lower surface of the coupling. Equation (1) shows that

1) When the acoustic wave reaches the upper surface of the coupling, the cross-sectional area changes from large to small, that is \( S_1 > S_2 \), the reflection coefficient is greater than 0, and the reflected wave signal is in phase with the incident (same polarity);

2) When the acoustic wave reaches the lower surface of the coupling, the cross-sectional area changes from small to large, that is \( S_1 < S_2 \), the reflection coefficient is less than 0, and the reflected wave signal is opposite to the incident (opposite polarity).

3. Analysis of response characteristics of acoustic wave propagation in oil casing annulus

In the detection of the dynamic fluid level depth, the accurate determination of the tubing coupling wave can effectively calculate the space acoustic velocity of the oil collar. In order to clarify the reflected wave shape of the coupling when the acoustic wave propagates downward in the oil jacket annulus, the corresponding three-dimensional model is constructed by the COMSOL finite element analysis software and the acoustic wave reflection characteristics are studied, as shown in Figure 2.

![Figure 2. Three-dimensional perspective view of coupling](image)

3.1. Numerical simulation and characteristic analysis of coupling reflected wave

In this part, the formation mechanism of the coupling wave and the coupling response under the excitation of different signal sources will be studied through numerical simulations.

3.1.1. Numerical simulation and characteristic analysis of abrupt cross-sectional area

In order to clarify the formation mechanism of the coupling wave, the upper and lower surfaces of the coupling are divided into two aspects to study, and a three-dimensional model of the abrupt cross-sectional area is constructed. The cross-sectional area of the tubing remains unchanged, and the cross-sectional area of the casing changes from large to small(Figure 3a); The cross-sectional area of the tubing remains unchanged, and the cross-sectional area of the casing changes from small to large(Figure 3b). The red area is the propagation medium of acoustic wave, and the yellow area is the tubing.

![Figure 3. Casing cross-sectional area from large to small (a) and small to large (b)](image)
When the cross-sectional area of the tubing remains unchanged, the cross-sectional area of the casing changes from large to small, that is $S_1 > S_2$, the reflection coefficient from equation (1) is greater than 0, that is, the two have the same polarity, then the reflected signal generated at the interface is the same as the incident signal. (Figure 4a). On the contrary, when the cross-sectional area changes from small to large, that is $S_1 < S_2$, the reflection coefficient is less than 0 from equation (1), that is, the two polarities are opposite. Then the reflected acoustic wave signal generated at this interface is the same as the incident the signal polarity is reversed (Figure 4b).

3.1.2. Numerical simulation and characteristic analysis of coupling response by different signal sources excitation

Figure 5 shows that under the excitation of positive signal source, the coupling reflected signal is positive (up) and then negative (descending) (Figure 5a); under the excitation of negative signal source, the coupling reflected signal is first negative (descending) and then positive (rising) (Figure 5b); under the excitation of positive and negative signal sources, the polarity of the first peak of the coupling reflected signal is consistent with that of the signal source, and the reflected signal is superimposed by the response generated by the excitation of negative and positive signal sources respectively (Figure 5c). When the acoustic waves reaches the coupling, it is equivalent to the cross-sectional area from large to small, and the polarity of the reflected signal is the same as that of the incident signal; when the acoustic signal leaves the lower interface of the coupling, the cross-sectional area increases from small to large, and the polarity of the reflected signal is opposite to that of the incident signal. Therefore, it can be concluded that the coupling signal is the superposition of the reflected signals from the upper and lower surfaces of the coupling. When the casing pressure is lower than 0.3MPa, the signal source is generated by the compressed air blasting of the external explosion device, which is close to the simulated negative signal source, then the actual coupling reflected wave waveform is consistent with the simulated negative signal source excitation; when the casing pressure is between 0.3MPa -5MPa, the signal source is generated by the compressed air blasting of the internal explosion device to generate a positive signal with the simulation If the signal source is close to each other, the actual coupling reflection waveform is consistent with that generated by the simulated positive signal
source.

3.2. Analysis of influencing factors of coupling reflected waveform
This part will study the influence of different coupling thickness, cross-sectional radius and pressure on the reflected waveform.

3.2.1. Influence on reflected waveform for different coupling thickness

In Figure 6, the fluid parameters, cross-sectional radius, pressure, and well depth of the oil sleeve are fixed. With the continuous increase of the thickness of the coupling, the peak-to-peak spacing of the coupling reflection wave becomes larger and the positive and negative peaks separate. This is because when the signal source propagates downward in the oil sleeve space, when it touches the upper interface of the coupling, the cross-sectional area changes from large to small and reflection occurs, and the reflected signal polarity formed is consistent with the signal source polarity. When contacting the lower interface of the coupling, the cross-sectional area changes from small to large, and reflection occurs. The polarity of the reflected signal formed is opposite to the polarity of the signal source. The reflected signals from the upper and lower interfaces are superimposed on each other to form a coupling signal. With the increase of the thickness of the coupling, the time difference between the reflection of the signal source at the upper and lower interfaces increases, resulting in an increase in the peak-to-peak spacing of the coupling signal and a change in the waveform.
3.2.2. Influence on reflected waveform for different cross-section radius of coupling

Figure 7. Response curve of reflected wave for different coupling radius (a) and Relationship between coupling radius and coupling reflected amplitude(b)

As the cross-sectional radius of the coupling increases, the peak value of the coupling wave shows an upward trend, and the waveform remains unchanged. The peak positions for different coupling radii are the same, and the amplitude increases as the coupling radius increases (Figure 7a). It can be seen from Figure 7b that the reflected wave amplitude of the coupling increases nonlinearly with the increase of the coupling radius.

3.2.3. Influence on coupling reflected waveform for different pressures

Figure 8. Response curve of coupling reflected wave for different pressures (a) and Relationship between pressure and amplitude (b)

As the pressure increases, the peak value of the coupling wave shows an upward trend. In Figure 8a, the peak positions for different pressures are the same, and the amplitude increases with the increase of the collar radius. It can be seen from Figure 8b that the amplitude of the reflected wave of the coupling increases linearly with the increase of the pressure in the oil casing annulus.

4. Conclusions

In this paper, the echo mechanism and morphology characteristics of acoustic wave generated by coupling when it propagates in the oil casing annulus under the excitation of different signal sources are studied. Numerical calculations of characteristics are made for the three factors of coupling thickness, coupling radius, and oil casing annulus pressure. And their influences on coupling waveform are analysed. It can be seen from figures that when the polarity of the signal source is positive (negative), the coupling reflected signal is first positive (negative) and then negative (positive); when the signal source is a positive and negative superposed source, the polarity of the first peak of the coupling reflected signal is consistent with that of the signal source, and the reflected signal is composed of the response generated by the excitation of the positive and negative signal sources, respectively. With the increase of the coupling radius, the coupling wave morphology remains unchanged, but the reflected wave amplitude increases nonlinearly with the increase of the coupling radius; with the increase of the space pressure of the oil jacket ring, the coupling wave morphology remains unchanged, but the reflected wave amplitude increases linearly with the increase of the oil.
casing annulus pressure; with the increasing of the coupling thickness, the coupling reflected wave peak to peak distance is larger and the positive and negative peaks are separated. The numerical simulations of acoustic wave reflection characteristics in the oil casing annulus reveals the reflection mechanism of coupling wave, which provides theoretical basis and reference standards for the characteristic analysis of the received signal by actual dynamic liquid level detector, the performance verification of the echo signal processing method and the correct identification of the dynamic fluid level position.

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References
[1] Li X.Y. (2016) Soft-sensor Modeling for Dynamic Fluid Level of Sucker-rod Pumping Process, Northeastern University.
[2] Nie S.T. (2014) The Research on the Soft-sensing Technique of Dynamic Liquid Level for Sucker Rod Pumping System Based on Multiple Models, Northeastern University.
[3] Wang T., Duan Z.W. (2019) Soft sensor modeling for dynamic liquid level of oil well based on fuzzy inference adaptive updating, CIESC Journal, 1-17.
[4] Li X.Y., Gao X.W., Cui Y.B., et al. (2013) Dynamic liquid level modeling of sucker-rod pumping systems based on Gaussian process regression, Ninth International Conference on Natural Computation (ICNC), Shenyang, China: IEEE, 2013: 917-922.
[5] Wang T., Gao X.W., Liu W.F. (2014) Adaptive soft sensor method and application in determination of dynamic fluid levels, CIESC Journal, 65(12): 4898-4904.
[6] Li X.Y., Gao X.W., Li K., et al. (2016) Ensemble soft sensor modeling for dynamic liquid level of oil well based on multi-source information feature fusion, CIESC Journal, 67(06): 2469-2479.
[7] Zhang P. (2016) Downhole liquid level depth detection research based on acoustic signal blind separation, Southwest University of Science and Technology.
[8] Liu Y.X., Yang Y.C., Han B.k., et al. (2015) Liquid level detection method of oil well with acoustic waves in a low frequency, Journal of Applied Acoustics, 34(01): 24-31.
[9] Zhou W., Jia W., Guo X.Y., et al. (2015) A New Method for Oil Well Dynamic Fluid Level Detection Based on the Column Sound Field Model, Journal of Southwest Petroleum University (Science & Technology Edition), 37(04): 166-172.
[10] Jia W. (2014) Research on a Detection Method of Oil Well Dynamic Fluid Level Based on the Column Sound Field Model, Xi'an Shiyou University.
[11] Du G.H., Zhou Z.M., Gong X.Z. (2012) Fundamentals of Acoustics, Nanjing University Press.