Numerical simulation of reflected wave characteristics in oil wells measured by Acoustic method

Ke Wang, Yanping Liu*, Jie Wu, and Jianshen Gao
Departments of Electronic Engineering, University of Xi’an Shiyou, Xi’an, Shaanxi, 710000, China
*Corresponding author’s e-mail: liuyp@xsyu.edu.cn

Abstract. In order to analyze and identify the corrosion of the inner interface of the coupling, perforating and casing, or the collapse and depression of the casing, as well as the reflection form of the dynamic liquid level, the COMSOL finite element analysis software was used to carry out numerical simulation research on the above situation, and its response characteristics were obtained through calculation. In this paper, three-dimensional propagation characteristics of acoustic waves in the annulus of the oil jacket were studied using signal sources of different polarities. The results showed that when the polarity of the signal source was positive (negative), the coupling reflection signal was first positive (negative) and then negative (positive), and the perforation reflection signal was first negative and then positive (positive then negative). The waveform of the reflection signal in the case of corrosion or casing collapse was consistent with the waveform of the perforation reflection signal; the reflection signal of the moving surface was of the same polarity as the emission signal source. When the signal source was a positive-negative superimposed source, the conclusion obtained by applying the above-mentioned positive (negative) polarized signal source was based on the polarity of the first peak of the superposed source. The research results can provide strong support for the popularization and improvement of related theories, and correct reference standards for the performance verification of echo processing methods, as well as important theoretical basis for the correct identification of echo positions on the Dynamic fluid interface.

1. Introduction
In recent years, many scholars have done a lot of research work on the detection of Dynamic fluid interface in oil wells, but lack of in-depth research on the mechanism and characteristics of echo generation. 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 sound 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 can not truly reflect the propagation characteristics of sound waves in tube-casing annulus. Airborne propagation characteristics. 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 lacking in 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 of the sound field characteristics, but did not further study the reflection characteristics of sound waves when propagating in the sound field model of the string. Up to now, the related research of sonic oil wells is mainly for the study of hydrodynamic surface measurement methods. There is no systematic research on the reflection mechanism and echo characteristics of acoustic waves when propagating in the air of the oil jacket ring. In addition, most of the methods for estimating the sound velocity and the method for detecting the hydrodynamic surface are directly applied to the measured data to draw conclusions. To identify the performance of a method requires a standard as a reference. This standard is the result of processing the ideal signal. However, the ideal signal needs to be obtained by analog methods as close to the real situation as possible. Based on this, the author uses COMSOL multiphysics simulation software to construct an annulus model of the oil jacket to simulate the reflection waves generated by the corrosion of the coupling, perforation, the inner interface of the casing or the collapse of the casing when the different signal sources are excited. Coupling waves and hydrodynamic surface waves. Conduct systematic research on the reflection characteristics of sound waves, analyze the mechanism and morphological characteristics of sound waves when they encounter different obstacles when they propagate in the air, and the 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 correctly identifying the echo position of the liquid surface.

2. Acoustic reflection theory of oil and gas wells

Figure 1 shows the physical model for oil and gas well measurement. Oil and gas wells consist of tubing connected by casing and couplings. The moving fluid level measuring instrument is installed at the wellhead. The pulsed sound source generated by the instrument propagates to the moving fluid level through the annulus between the casing and the tubing. The sound wave receiving sensor collects the sound waves of the annulus, the moving fluid level and the surrounding oil well at a certain sampling rate. Reflected signal. Because the length of the tubing is fixed, by measuring the periodic reflection signal time of the coupling, the propagation speed of the sound waves in the annulus can be determined. The speed multiplied by the single-pass reflection time of the moving liquid surface is equal to the depth of the moving liquid surface. This is the basic principle of moving liquid surface measurement. The core is to determine the position of the hydrodynamic surface and calculate the speed of sound. The basic theory of acoustic wave propagation in oil and gas wells is analyzed below.

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

![Figure 2. Three-dimensional perspective view of the coupling (b), perforation (c), and depression of the inner interface of the casing (d)]

2.1. Principle of reflection of acoustic signals in annulus of oil jacket

The reflection of a hydrodynamic surface acoustic wave signal is equivalent to the normal incidence of the acoustic wave signal at the interface of two different impedances. At this time, the law of sound pressure and sound velocity reflection and transmission [11] is

$$ r_p = \frac{R_2 - R_1}{R_1 + R_2} \quad (1) $$

$$ r_v = \frac{R_1 - R_2}{R_1 + R_2} \quad (2) $$

$$ t_p = \frac{2R_2}{R_1 + R_2} \quad (3) $$

$$ t_v = \frac{2R_1}{R_1 + R_2} \quad (4) $$
In equations (1) and (2), $r_p(r_v)$ and $t_p(t_v)$ are the reflection and transmission coefficients of sound pressure (velocity of sound), $R_1$ and $R_2$ are the acoustic impedances of medium 1 (annulus) and medium 2 (oil-gas-water). $R_1 = \rho_1 c_1$, $R_2 = \rho_2 c_2$, $\rho$ and $c$ are the density and sound velocity of the medium (annulus, oil-gas-water), respectively. Equations (1) and (2) show:

1) In normal oil and gas wells, the speed of sound in the oil and water is much greater than the speed of sound in the annulus, therefore $R_2 \gg R_1$. Substituting (1) to (4) gives 1, -1, 2 and 0. It shows that the total speed of sound occurs on the interface, and the sound pressure continues to propagate in a static pressure manner.

2) When sound waves pass through the perforated water outlet layer of the oil and gas surface to reach the water outlet layer, $R_2 > R_1$. The sound pressure reflection coefficient is greater than 0 and the velocity reflection coefficient is less than zero. Conversely, when passing through the water layer, $R_1 > R_2$, negative sound pressure, the sound pressure of the reflected wave is opposite to the sound pressure of the incident wave, and the sound velocity is greater than 0.

2.2. Coupling, perforating, and sinking signal reflection principles

When a sound wave passes through a coupling with a changed cross section, the reflection coefficient of the sound pressure can be described by reflection formulas with different cross-sectional area parameters [11]:

$$r_p = \frac{S_1 - S_2}{S_1 + S_2} (5)$$

In formula (5), $S_1$ and $S_2$ are the cross-sectional areas of the upper and lower surfaces of the coupling, perforation, and depression. Equation (5) shows:

1) On the upper surface of the coupling, the perforation or the recessed lower disk, the area changes from large to small, that is $S_1 > S_2$, the reflection coefficient is greater than 1, and the reflected wave signal is in the same phase (same polarity) as the incident;

2) On the lower surface of the coupling, the perforation or the recessed upper disk, the area changes from small to large, that is $S_1 < S_2$, the reflection coefficient is less than 1, and the reflected wave signal is opposite to the incident (opposite polarity).

3. Forward model construction and result analysis

In order to clarify the corrosion of couplings, perforations, casing internal interfaces or casing collapse depressions and liquid surface reflection wave shapes, corresponding three-dimensional models were constructed and their acoustic reflection characteristics were studied, as shown in Figure 2.

3.1. Numerical simulation and characteristic analysis of coupling reflection wave using COMSOL software

In order to clarify the coupling wave formation mechanism, the upper and lower surfaces of the coupling are divided into two aspects to study, and a three-dimensional three-dimensional model of the abrupt cross-sectional area is constructed: 1 The cross-sectional area of the tubing remains unchanged, and the cross-sectional area of the casing changes from large to small (Figure 3a); 2 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 acoustic wave propagation medium, and the yellow area is the oil pipe.

Figure 3. Casing cross-sectional area from large to small (a) and small to large (b)
Figure 5. Coupling sound wave response under positive excitation (a), negative (b), and positive and negative superimposed (c) excitation

Figure 5 shows: the positive signal source is excited, the coupling reflection signal is positive (rise) and then negative (falling) (Figure 5a); the negative signal source is excited, the coupling reflection signal is negative (falling) first and then positive (rising) (Figure 5b). Positive and negative superimposed signal source excitation, the polarity of the first peak of the coupling reflection signal is consistent with the signal source, and its reflection signal is superimposed by the responses generated by the negative and positive signal sources respectively (Figure 5c). When the sound wave 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; when the sound wave signal leaves the lower interface of the coupling, the cross-sectional area is from small to large, and the polarity of the reflected signal is opposite to the incident. The available coupling signals are obtained by superimposing the two signals.

3.2. Numerical simulation and characteristic analysis of perforated reflected waves using COMSOL software

Figure 6. Positive wave source (a), negative signal source (b) and positive and negative superimposed signal source (c) excited perforated acoustic wave response

Figure 6 shows that the positive signal source excites and the perforated reflection signal is negative (falling) and then positive (rising) (Figure 6a); the negative signal source excites and the perforating reflection signal is positive (rising) and then negative (falling) (Figure 6b); the positive and negative superimposed signal sources are excited, and the polarities of the first peak of the perforated reflected signal are opposite to the signal source, and the reflected signals are superimposed by the responses generated by the negative and positive signal sources, respectively (Figure 6c). When the acoustic...
wave reaches the upper interface of the perforation, the equivalent of the cross-sectional area is from small to large, and the polarity of the reflected signal is opposite to that of the incident. When the acoustic wave leaves the lower interface of the perforation, the cross-sectional area is from large to small, and the polarity of the reflected signal is the same as that of the incident. It can be obtained that the perforation signal is obtained by superimposing the two signals.

3.3. Using COMSOL software to perform numerical simulation and characteristic analysis of the reflected wave when the internal interface of the casing is corroded or the casing collapses and sags

![Figure 7](image_url)

Figure 7. Sag response of a positive signal source (a), a negative signal source (b), and a positive and negative superimposed signal source (c)

Figure 7 shows that the positive signal source excites and the concave reflection signal is negative (falling) and then positive (rising) (Figure 7a); the negative signal source excites and the concave reflection signal is positive (rising) and then negative (falling) (Figure 7b); Positive and negative superimposed signal sources are excited. The polarity of the first peak of the concave reflection signal is opposite to that of the signal source, and its reflected signal is superimposed by the responses generated by the negative and positive signal sources respectively (Figure 7c). When the sound wave reaches the upper interface of the depression, it is equivalent to the cross-sectional area from small to large, and the polarity of the reflected signal is opposite to the incident. When the sound wave leaves the lower interface of the depression, the cross-sectional area is from large to small, and the reflected signal has the same polarity as the incident. The available sag signals are obtained by superimposing the two signals.

3.4. Using COMSOL software to carry out numerical simulation and characteristic analysis of the reflected waves in the annular space of the oil jacket

![Figure 8](image_url)

Figure 8. Acoustic response in the presence of couplings, perforations, and depressions

Figure 8 shows that: under the excitation of a positive signal source, the coupling reflection signal is positive (rising) and then negative (falling); the perforated reflection signal is completely opposite, negative and then positive; the shape of the concave reflection signal is basically the same as the perforated reflection signal; The signal of the hydrodynamic surface reflects the same polarity as the emission. When the acoustic wave 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. When the acoustic wave leaves the lower interface of the coupling, the cross-sectional area is from small to large, and the polarity of the reflected signal is opposite to the incident. When a sound wave passes through a perforation or depression, the cross-sectional area is from small to large, and then from large to small, as opposed to a coupling. At the interface of the hydrodynamic surface, the sound wave is incident from the air with a small wave impedance to the oil and gas interface with a large wave impedance. According to Equation (1), the sound wave is approximately totally reflected and has the same polarity as the transmitted signal.
4. Conclusions
In this paper, under different signal source conditions, COMSOL software is used to numerically simulate the reflected waves generated by the corrosion of the inner interface of the coupling, perforation and casing or the collapse of the casing, and the simulation data is analyzed in detail. It can be known that when the polarity of the signal source is positive (negative), the coupling reflection signal is first positive (negative) and then negative (positive), and the perforation reflection signal is first negative and then positive (positive and then negative); The waveform of the reflected signal in the case of corrosion of the internal interface of the casing or the collapse of the casing is consistent with the waveform of the perforated reflection; the dynamic fluid interface reflection signal and transmitting signal source have the same polarity. When the signal source is a positive-negative superimposed source, the conclusion obtained by applying the above-mentioned positive (negative) polarized signal source is based on the polarity of the first peak of the superposed source. The numerical simulation of the reflection characteristics of the sound waves in the air of the oil jacket ring reveals the reflection mechanism of the coupling wave and the hydrodynamic surface wave in the case of corrosion of the inner interface of the coupling, perforation, and casing, or the collapse of the casing. The characteristics analysis of the signal received by the instrument, the performance verification of the echo signal processing method, and the correct identification of the position of the hydrodynamic surface provide theoretical basis and reference standards.

Acknowledgments
This research was financially supported by National Natural Science Foundation of China (Program No. 41704106, 41804115), The Project Supported by Natural Science Basic Research plan in Shaanxi Province of China (Program No. 2018JQ4045, 2018JQ4008), and Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No. 19JK0665).

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.