Acoustics Tomography Simulation for Probing Oil Reservoir

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Abstract. In oil exploration, the acoustic wave is usually generated by the hammer stroke method and then propagates to the interior of the formation. Finally, the information of oil reservoirs is obtained by inverting the reflected compressional waves. In order to make full use of the echoes, we use the reflected shear wave to inverse the compressional wave velocity and compare it with the actual measured compressional wave velocity to serve as a quicklook oil detection. COMSOL Multiphysics, based on the finite element analysis, is used to simulate the propagation process of ultrasonic waves in the physical model, which is different from the previous simulation methods. Moreover, it can provide data for other imaging algorithms quickly.

1. Introduction
The seismic exploration usually employs explosives or heavy hammers to generate infrasound waves propagating in earth. Then different reflection signals are acquired from soil layer junctions of different compositions. Seismic compressional waves have been primarily used in seismic exploration. The compressional wave has some outstanding merits such as easy occurring, simple waveform and fast propagation speed. Besides, the seismic shear waves, of which the propagation direction is perpendicular to its vibration direction, also have inherent advantages in judging the properties of lithology, cracks and hydrocarbon. Different from the compressed waves, the shear waves are not affected by groundwater and usually used in stratum fracture identification. Shear wave imaging can achieve higher and more accurate resolution in seismic exploration imaging [1]. Moreover, the abundant waveform information of shear waves provides an effective method for the exploration of carbonate rocks, cracks and complex structures. The shear wave data will provide a clearer and more accurate geological interpretation for the underground geological problems.

The previous geophysical simulations are usually processed as path integrals, in which the imaged region is partitioned into cells and the corresponding slowness is specified by a single parameter [2]. Accordingly, some classic reconstruction methods have been proposed, such as algorithms of the algebraic reconstruction technique and the simultaneous iterative reconstruction technique. Even more, Algebraic methods have also been proposed to optimize the calculation results, in which the wave field is propagated through the currently known slow field, and then the estimated Jacobian matrix is calculated through a linearization problem.

Most of the above geophysical simulations are based on the propagation rules of compressed waves. In this paper, we combine the seismic waveform information of compressed and shear waves to invert the more accurate geological compositions in COMSOL Multiphysics simulation. Besides, it can provide convenient seismic simulation data for actual exploration structure or the seismic physical model.
2. Theoretical bases for simulations

Assuming that elastic deformation occurs in the formation, COMSOL’s groundwater flow module and solid mechanics interface can be used for simulation. Groundwater flow in porous media is described by Darcy's law and continuity equation,

$$\nabla \cdot ( - \kappa \frac{\nabla p}{\mu} ) = 0$$

(1)

where $\kappa$ is the permeability coefficient, $\mu$ is the dynamic viscosity coefficient, and $p$ is the pressure of oil in the pores.

For the flow boundaries, oil is stored under the surface of the earth, so no flow boundary conditions are available at the oil boundary, which can be expressed as

$$\mathbf{n} \cdot \left( - \kappa \frac{\nabla p}{\mu} \right) = 0$$

(2)

where $\mathbf{n}$ is the normal vector of the boundary.

The equation describing quasi-static deformation is

$$- \nabla \cdot \sigma = \mathbf{F}$$

(3)

where $\sigma$ represents the stress tensor and $\mathbf{F}$ is the external strength. Pressure loaded on the pore makes the stress tensor increase. In this model, Biot-Willis coefficient is equal to 1. Model reference pressure is $1 \times 10^5 \text{Pa}$, temperature is 273 K.

The stress-strain relation of linear materials involves stress tensors $\varepsilon$ and strains. In this model, the component of the stress tensor depends on the displacement vector $\mathbf{u}$, which has three directions $u$, $v$, $w$.

$$\varepsilon_{11} = \frac{\partial u}{\partial x}$$

$$\varepsilon_{22} = \frac{\partial v}{\partial y}$$

$$\varepsilon_{33} = \frac{\partial w}{\partial z}$$

$$\varepsilon_{12} = \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)$$

$$\varepsilon_{23} = \frac{1}{2} \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)$$

$$\varepsilon_{31} = \frac{1}{2} \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)$$

(4)

For the boundary condition, we select low-reflecting boundary to simulate an infinite underground.

3. Elastic waves propagate in solid medium

In the experiment, organic materials are usually used as the seismic physical model, so we use three layers of polymer materials, respectively acrylic plastic, PMMA, acrylic plastic.

![Diagram of the geometric model](image)

Fig. 1. The geometric model consists of three layers of polymer materials, including acrylic plastic, PMMA, and acrylic plastic.
This is a two-dimensional model of a formation where a displacement point is placed on the surface to generate an elastic wave signal that propagates down the model.

![Graph](image1.png)

Fig. 2. The displacement point in Fig. 1 vibrates according to the acoustic function.

![Graph](image2.png)

Fig. 3. The stress tensor at a certain location is measured by putting a probe into the model. (a) It represents the stress tensor 11 signal, which can be approximated as a compressional wave signal. (b) It represents the stress tensor 13 signal, which can be approximated as a shear wave signal.
Fig. 4. The propagation processes of the compressed and shear waves. The green lines present shear waves. The blue lines present compressional waves. ① is the incident shear wave. The incident compressional wave is reflected and transmitted. ② and ③ are the compressional and shear waves conversed by reflected compressional waves at different media interfaces. ④ and ⑤ are the compressional and shear waves conversed by transmitted compressional waves at different media interfaces.

Since sound waves are elastic waves, there are compressional waves and shear waves below the surface, such as figure a. When ultrasonic wave propagates to the interface between acrylic plastic and PMMA, reflection and refraction will occur as figure b. Because compressional wave and shear wave interconvert at the interface of different materials, we can see that both the reflected and refracted waves have two kinds of waves.

Fig. 5. Imaging of the different material interfaces using compressional and shear waves in Fig. 4, respectively.

4. Elastic waves propagate in porosity medium
Reservoir rock is a porous medium, which can be filled with water, gas and other fluids. The existence of fluids will affect the seismic parameter characteristics of rocks. If the relationship between the overall properties of rocks and porosity and pore fluid can be known, the rock properties can be reflected by the formation wave velocity to investigate the existence of underground fluids.
Understanding of reservoir characteristics (such as porosity, permeability) and pore fluid state (fluid saturation) is the key to reservoir evaluation and oil and gas recovery [3].

Fig. 6. For rocks with different porosity size, the greater the porosity, the lower the compressional wave velocity.

Fig. 7. The compressed velocities of PMMA and acrylic plastic vary with the porosity sizes, corresponding to Fig. 6.

According to Biot theory and Darcy’s law, the pore fluid increases the compressional wave velocity and decreases the shear wave velocity.

The effect of porosity on \( V_p \) is greater than that on \( V_s \), because the shear wave mainly propagates along the rock skeleton, and the velocity has little relationship with the pore fluid properties. When the rock porosity is small, the content in the rock is independent of the shear wave velocity [4].

Fig. 8. The velocity ratios of the compressional wave and shear wave are obviously different in different types of formation fluids, where the slowness is the reciprocal of the acoustic velocity.
The quicklook oil detection technique we simulated uses polynomial best fits to the trends on the compressional slowness versus shear slowness crossplot in different porosities,

\[ \Delta p = C_0 + C_1 \Delta s + C_2 \Delta s^2 + C_3 \Delta s^3 + C_4 \Delta s^4 + C_5 \Delta s^5 + C_6 \Delta s^6 \]

where \( \Delta s \) is the theoretical shear wave slowness in the materials, \( \Delta p \) is theoretical compressional slowness in the water. The coefficients \( C_i \) are adjusted to fit the sand trends for different agrotype and fluid types. The advantage of this approximation method is that best fit routines for polynomial approximations are widely available and the goodness of fit is excellent.

If the formation fluid types are different, the compressional and shear wave velocity ratios are significantly different. The oil and gas characteristics of the formation can be identified by using the compressional and shear wave velocity ratios [5].

Therefore, the compressional wave velocity of water in the pores of the material can be inversely calculated by measuring the shear wave velocity of the material through the polynomial, and based on the comparison of the actually measured longitudinal wave velocity, it can be used in the quicklook oil detection.

Fig. 9. The black line represents the compressional wave velocity of the water in the pores inversely calculating the shear wave slowness. The red line represents the actually calculated pore velocity as the compressional wave velocity of the oil. In the yellow area, the two lines do not overlap with each other, indicating that the pore filling is oil, not water.

In this porous medium model, acrylic plastic and PMMA have a porosity of 0.2 and the permeability is \(1 \times 10^{-6} cm^2\). Place a probe every 0.05cm inside the model for recording sound wave information under the sound source. Analyse the information of the signal of each probe. The difference in probe position causes receiving time different. Because the proximity distance of adjacent probes is known, the acoustic slowness of different materials can be obtained.

5. Conclusion
In conclusion, we propose a comprehensive solution for the geological simulation of acoustic propagation in different physical structures by combining the seismic propagations of both the compressed and shear waves. It helps to obtain more accurate geological formation, and even to distinguish the pore filling (water or oil). This simulation approach based on COMSOL Multiphysics provides a quicklook for oil detection.

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