Analysis of Velocity dispersion and Attenuation in Double-scale Model

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Abstract. In the two states of oil-gas and water-gas, the wave velocity and attenuation coefficient are numerically simulated by double-scale model. The P-wave velocity and attenuation coefficient curves show double-step and double-peak, respectively. With the increase of gas saturation, the velocity step of mesoscopic scale gradually decreases and disappears. The attenuation peak decreases and the characteristic frequency shifts to high frequency until it coincides with the characteristic frequency of the micro-scale. The superposition of the attenuation peak makes the total attenuation peak increase. And there is a great difference in fluid properties when oil, gas and water are mixed in the reservoir, so the double-scale model can better predict the fluid saturation in the reservoir and better monitor the fluid.

Keywords: Velocity dispersion; Attenuation coefficient; Double-scale model.

1. Introduction
There are a variety of geophysical exploration methods, and the main frequency bands of different exploration methods are also different. The main mechanism of attenuation of seismic waves in different frequency bands is also different. When the seismic wave propagates in the reservoir, the pore fluid usually produces squirt flow, which is considered to be the main coefficient leading to the velocity dispersion. Mavko-Jizba [1, 2] established the squirt model under the high frequency limit condition. Gurevich [3] optimized the high frequency limit squirt model by Sayers-Kachanov formula and anisotropic Gassmann equation. The model can be applied to saturated and dry rock and mainly reflects the dispersion and attenuation of Ultrasonic frequency bands. White [4] established the periodic spherical patch model for the first time. Based on the spherical patch model, the layered patch saturation model was established, which mainly reflects the dispersion and attenuation of seismic frequency bands. Therefore, it is necessary to establish a multi-scale numerical simulation model and consider the attenuation mechanism in different frequency bands at the same time.

2. Theory of Mesoscopic-Microscopic Double-scale model
In fluid-containing porous media, there are two different flow modes: relative flow and squirt flow, corresponding to different scales and frequency bands, respectively. When the medium is under the condition of low frequency limit, the pore fluid has enough time to flow so that the pore pressure balance can be reached inside the pore, that is, the fluid in the soft pore will flow to the hard pore, and its elastic
modulus is obtained by Gassmann equation. While under the condition of high frequency limit, the pore fluid cannot reach equilibrium in half a wavelength period, so that the pore pressure is in an unrelaxed state, the bulk modulus of the medium will increase, and the elastic modulus will also increase. When the relative flow of fluid occurs in the medium, the bulk modulus of the medium is between the high frequency limit and the low frequency limit, which has the phenomenon of dispersion, so the attenuation mechanism of two different frequency bands is combined. It is necessary to explain the dispersion and attenuation of elastic velocity in the full frequency band. When establishing the double-scale model, dry modulus of the frequency squirt medium is used to replace dry modulus of low frequency limit obtained by Gassmann equation.

\[
\frac{1}{K_{nf}(\omega)} = \frac{1}{K_n} + \frac{1}{K_s} \left( \frac{1}{K_f(\omega)} - \frac{1}{K_r} \right) \varphi,
\]

(1)

\[
\frac{1}{\mu_{nf}(\omega)} = \frac{1}{\mu_n} - \frac{4}{15} \left( \frac{1}{K_n} - \frac{1}{K_{nf}(\omega)} \right)
\]

(2)

Of which:

\[
\alpha(\omega) = -K_{nf}(\omega)
\]

(3)

\[
\mu(\omega) = \mu_{nf}(\omega)
\]

(4)

\[
\frac{1}{D(\omega)} = 2 \left[ \alpha(\omega) \frac{1}{K_r} + \phi \left( \frac{1}{K_f(\omega)} - \frac{1}{K_r} \right) \right]
\]

(5)

\[
K(\omega) = K_{nf}(\omega) + 2\alpha^2(\omega)D(\omega)
\]

(6)

\[
\lambda(\omega) = K(\omega) - \frac{2}{3} \mu(\omega) + 2\alpha^2D(\omega)
\]

(7)

\[
H(\omega) = K(\omega) + \frac{4\mu(\omega)}{3}
\]

(8)

These coefficient expressions are substituted into the constitutive equation and motion equation of the patch saturation model:

\[
\rho_b \frac{\partial^2 \vec{u}}{\partial t^2} + \rho_f \frac{\partial^2 \vec{w}}{\partial t^2} = H \nabla (\nabla \cdot \vec{u}) + 2\alpha(\omega)D(\omega) \nabla (\nabla \cdot \vec{w})
\]

(9)

\[
\rho_f \frac{\partial^2 \vec{u}}{\partial t^2} + m \frac{\partial^2 \vec{w}}{\partial t^2} = 2\alpha(\omega)D(\omega) \nabla (\nabla \cdot \vec{u}) + 2D(\omega) \nabla (\nabla \cdot \vec{w}) - \frac{\eta}{\kappa} \frac{\partial \vec{w}}{\partial t}
\]

(10)

\[
\tau = H(\omega) \frac{\partial \vec{u}}{\partial r} + 2\lambda(\omega) \frac{\vec{u}}{r} + 2\alpha(\omega)D(\omega) \left( \frac{\partial \vec{w}}{\partial r} + \frac{2}{r} \vec{w} \right)
\]

(11)

The solution process of the improved double-scale model is consistent with that of the normal patch model, so the solution of the elastic wave can be obtained by solving the model through the previous solution process [5].

3. Numerical simulation of different models

3.1. BISQ Model

Using the same set of petrophysical parameters to simulate the velocity dispersion and attenuation according to different models. The effects of different parameters on dispersion and attenuation are analyzed. The specific parameters are shown in Table 1.
Table 1. Petrophysical parameters of the model

| Bulk modulus | Shear modulus | Density    | Fluid modulus       |
|--------------|---------------|------------|---------------------|
| 4.5 GPa      | 3.5 GPa       | 2650 kg/m³ | 2.2/1.8/0.02 GPa    |

(1) Aspect ratio
Four aspect ratio values of 0.0008, 0.0012, 0.0018 and 0.0022 are selected to simulate the wave velocity and attenuation coefficient, corresponding to the black, red, blue and green curves in the figure, as shown in Fig. 2.1.

![Fig. 1](image)

Fig. 1 a) Wave velocity b) Attenuation coefficient

At the same aspect ratio, the velocity increases with the increase of frequency, and the attenuation coefficient increases at first and then decreases. For the same frequency, the larger the pore aspect ratio is, the smaller the low frequency velocity and high frequency velocity. The weaker the velocity dispersion is, the frequency of the velocity dispersion will move to the high frequency direction, and the peak value of the attenuation coefficient decreases. And the characteristic frequency moves to high frequency.

(2) Soft porosity
Four soft porosity values of 0.0001, 0.0005, 0.0005, 0.0015 and 0.002 are mainly selected, while the hard porosity remains unchanged. The velocity dispersion and attenuation coefficient are numerically simulated as shown in Fig. 2.2, corresponding to black, red, blue and green curves, respectively.

![Fig. 2](image)

Fig. 2 a) Wave velocity b) Attenuation coefficient

For the same soft porosity, the velocity increases with the increase of frequency. For different soft porosity, the velocity decreases and the peak value of attenuation coefficient increases with the increase of soft porosity at the same frequency. This corresponds to the changing trend of velocity with soft porosity, and the peak value of attenuation coefficient does not shift with the change of soft porosity, which is consistent with the formula of characteristic frequency.
3.2. White’s Model

(1) Permeability

Select four sets of permeability values, 100mD, 200mD, 315mD and 400mD corresponding to the blue, green, red and black curves in the diagram, as shown in figure 2.3.

![Fig. 3 a) wave velocity b) Attenuation coefficient](image)

At the same frequency, with the increase of permeability, the dispersion of velocity does not change, but the frequency of initial dispersion moves to high frequency; it can be found that the characteristic frequency moves to high frequency with the increase of permeability. The peak value of attenuation does not change with the change of permeability.

(2) Gas saturation

The selected gas saturation is 10%, 20%, 50% and 80%, respectively, corresponding to the blue, red, green and black curves in the figure, as shown in Fig. 2.4

![Fig. 4 a) Wave velocity, b) Attenuation coefficient](image)

When the gas saturation is different, the initial velocity is different. It can be found that when the gas saturation is 10%, the dispersion of velocity is the largest, and with the increase of gas saturation, the dispersion of velocity decreases gradually, and when the gas saturation is 80%, the dispersion of velocity becomes very small. By observing the attenuation curve, it is found that with the increase of gas saturation, the characteristic frequency moves to high frequency and the peak value decreases gradually. This is due to the larger the porosity, the smaller the attenuation, which is consistent with the gradual decrease of velocity dispersion.

3.3. Double-scale model

The velocity and attenuation are numerically simulated when the gas saturation of the reservoir is 10%, 40% and 90%, respectively, and the results are shown in the blue curve, red curve and yellow curve in Fig. 2.5 and Fig. 2.6, respectively.

(1) Water-Gas
At different gas saturation, the limit velocity of high and low frequency remains the same and increases with the increase of frequency, and the velocity shows a double-step. With the increase of gas saturation, the mesoscale step decreases gradually, the double-step weakens and disappears. The frequency of velocity dispersion begins to shift to high frequency, which is due to the velocity dispersion effect of mesoscopic scale decreases with the increase of gas saturation.

The attenuation curve shows a double-peak. With the increase of gas saturation, the peak value of mesoscopic scale decreases, the characteristic frequency shifts to high frequency until it coincides with the microscopic characteristic frequency. While the peak value of micro-scale increases, and the characteristic frequency does not shift. This is because with the increase of gas saturation, the attenuation caused by the mesoscale wave-induced flow mechanism decreases and the characteristic frequency shifts to high frequency, until it coincides with the characteristic frequency of the micro scale, the attenuation peak is superimposed with the attenuation peak of the micro scale, so that the total attenuation peak increases.

4. Summary
Compared with the single-scale attenuation model, the double-scale model can better predict the fluid type and saturation in the reservoir according to the velocity and attenuation coefficient curve of different fluids and saturation simulation. When oil-gas and water-gas are mixed in the reservoir, there is a great difference in fluid properties between water-gas and oil-gas, and the double-scale model can be used to monitor the fluid better.
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