Journal of Applied Geophysics 150 (2018) 126–143

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Effective modeling and reverse-time migration for novel pure acoustic wave in arbitrary orthorhombic anisotropic media

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A R T I C L E   I N F O

Article history:
Received 5 April 2017
Received in revised form 29 October 2017
Accepted 17 January 2018
Available online 31 January 2018

Keywords:
Anisotropy
Acoustic wave equation
Finite-difference
Numerical modeling
Graphic processing unit (GPU)
Reverse-time migration (RTM)

A B S T R A C T

The conventional pseudo-acoustic wave equations (PWEs) in arbitrary orthorhombic anisotropic (OA) media usually have coupled P- and SV-wave modes. These coupled equations may introduce strong SV-wave artifacts and numerical instabilities in P-wave simulation results and reverse-time migration (RTM) profiles. However, pure acoustic wave equations (PAWEs) completely decouple the P-wave component from the full elastic wavefield and naturally solve all the aforementioned problems. In this article, we present a novel PAWE in arbitrary OA media and compare it with the conventional coupled PWEs. Through decomposing the solution of the corresponding eigenvalue equation for the original PWE into an ellipsoidal differential operator (EDO) and an ellipsoidal scalar operator (ESO), the new PAWE in time-space domain is constructed by applying the combination of these two solvable operators and can effectively describe P-wave features in arbitrary OA media. Furthermore, we adopt the optimal finite-difference method (FDM) to solve the newly derived PAWE. In addition, the three-dimensional (3D) hybrid absorbing boundary condition (HABC) with some reasonable modifications is developed for reducing artificial edge reflections in anisotropic media. To improve computational efficiency in 3D case, we adopt graphic processing unit (GPU) with Compute Unified Device Architecture (CUDA) instead of traditional central processing unit (CPU) architecture. Several numerical experiments for arbitrary OA models confirm that the proposed schemes can produce pure, stable and accurate P-wave modeling results and RTM images with higher computational efficiency. Moreover, the 3D numerical simulations can provide us with a comprehensive and real description of wave propagation.

1. Introduction

Reverse-time migration (RTM) in multi-dimensional transversely isotropic (TI) media has played a significant role in seismic data processing and interpretation of exploration seismology (e.g., Du et al., 2007; Fletcher et al., 2009; Zhang and Zhang, 2008, 2011; Zhang et al., 2011; Duveneck and Bakker, 2011). A core technology for the high-resolution RTM is to use accurate and efficient two-way wave equations (TWWEs) in forward, reconstructed and backward wavefield extrapolation stages. Generally, the combination of different properties in the independent TI media can be represented by orthorhombic anisotropic (OA) media with three mutually orthogonal planes of the mirror symmetry. That is, the symmetry of OA media is more general than TI media. Furthermore, this type of anisotropic media can be observed in fractured zones where a set of vertical fractures is embedded in vertical transversely isotropic (VTI) media (Tsvankin and Grechka, 2011).

In practice, the elastic TWWEs are seldom involved in implementation of anisotropic RTM for their expensive computational cost and wavefield complexity (e.g., Yan and Sava, 2011; Cheng and Fomel, 2014; Wang et al., 2016). Alternatively, Alkhalifah (2000) proposed an acoustic wave equation for VTI media using zero vertical S-wave velocity. Later on, Alkhalifah (2003) adopted the same pseudo-acoustic approximation to achieve an acoustic wave equation of sixth-order mixed derivatives in vertical orthorhombic anisotropic (VOA) media. Following Alkhalifah's works, different variants of pseudo-acoustic wave equations (PWEs) in TI media get further developments (e.g., Zhou et al., 2006a, 2006b; Du et al., 2008; Fowler et al., 2010; Duveneck and Bakker, 2011; Zhang et al., 2011). Fowler and King (2011) proposed coupled partial differential equations for PWE in OA media based on their previous achievements in TI media (Fowler et al., 2010). Zhang and Zhang (2011) developed self-adjoint differential operators in titled transversely isotropic (TTI) media (e.g., Duveneck and Bakker, 2011; Zhang et al., 2011) to arbitrary OA media, including VOA media and titled orthorhombic anisotropic (TOA) media.

Unfortunately, there are several critical problems about PWEs in anisotropic media. The prerequisite of PWEs derived from pseudo-acoustic

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https://doi.org/10.1016/j.jappgeo.2018.01.013

approximation in TI media is Thomsen's anisotropy parameters $\varepsilon \geq \delta$. However, not all physical parameters satisfy this precondition in practice (e.g., Thomsen, 1986; Wang, 2002). In addition, when TTI media have large variations inclination or azimuth angle, the corresponding PWEs will become unstable (e.g., Zhou et al., 2006b; Fletcher et al., 2009) and arise inevitable noises (e.g., Duveneck and Bakker, 2011; Zhang et al., 2011). Furthermore, setting the vertical S-wave velocity to zero doesn't completely suppress the SV-waves in all directions (Grechka and Tsvankin, 2004). It can result in instabilities and uncertainties in P-wave simulation results and RTM images. Accordingly, many scholars proposed different strategies to address these issues, such as setting isotropic or elliptic anisotropic material surround the source (Alkhalifah, 2000), smoothing the anisotropy parameters model (Zhang and Zhang, 2008), introducing restrictive vertical S-wave velocities (Fletcher et al., 2009) or applying noise suppressing filters (e.g., Zhang et al., 2009; Guan et al., 2011) and so on. However, these operations can't fundamentally eliminate SV-wave artifacts and numerical instabilities.

Developing pure acoustic wave equations (PAWEs) in anisotropic media can thoroughly solve the above-mentioned issues. Liu et al. (2009) derived independent P- and SV-TWWEs in VTI media through decoupling the P-SV dispersion relation. Then, several numerical algorithms are proposed to solve the decoupled PAWEs with complicated spatial pseudo differential operator (SPDO) in TI media (e.g., Etgen and Brandsberg-Dahl, 2009; Crawley et al., 2010; Du et al., 2010; Chu et al., 2011, 2013; Yan and Liu, 2016). Zhan et al. (2012) calculated the SPDO in wavenumber domain individually by the pseudo-spectral method (PSM) and then employed the rapid-expansion-method (REM). Fomel et al. (2013) and Wu and Alkhalifah (2014) adopted low-rank approximation method (LAM) to solve the PAWEs. Waheed and Alkhalifah (2014) applied the effective isotropic approximations to simulate PAWEs with lower computational cost. Frankly, these methods are still compromises between accuracy and efficiency. Xu and Zhou (2014) introduced an alternative approach to solve the PAWE in TI media (Alkhalifah, 2000). Through decomposing the original SPDO into a Laplacian operator and a scalar operator, these two operators can be combined into a new PAWE. The computational efficiency of the new PAWE can be significantly improved compared with some spectral-based methods. Nevertheless, numerical errors and amplitude distortions can be observed in the axial directions and high wavenumber regions (e.g., Xu and Zhou, 2014; Tang et al., 2014), especially for TTI media with a high dip angle. To handle these problems, Xu et al. (2015) decomposed the SPDO into an ellipsoidal differential operator (EDO) and an ellipsoidal scalar operator (ESO) that matches the phase of the Alkhalifah (2000)'s equation in TI media. After these modifications, the ellipsoidal decomposition method (EDM) can yield better tolerance to the direction errors and more balanced amplitude than the spherical decomposition method (SDM) (Xu and Zhou, 2014). For acoustic wave equation in OA media, Song and Alkhalifah (2013) derived a dispersion relation for pseudo-acoustic OA media and then applied LAM to space-wavenumber domain operators. Le and Levin (2014) removed SV-wave artifacts in P-wave wavefield through a wavenumber-domain eigenvalue decomposition of the SPDO in VOA media. The computational costs of these methods are expensive. Waheed and Alkhalifah (2016) computed effective ellipsoidal models by fitting kinematic features corresponding to the original TOA media and achieved much cheaper wave extrapolation operators. The “effective model” can greatly generate a significant improvement of computational efficiency, but the qualities of RTM image rely on whether the dominated imaging energies of wavefields are on the first arrival. Consequently, this study will focus on pure acoustic wave wavefield in arbitrary OA media. Moreover, to speed up computation for three-dimensional (3D) case, graphic processing unit (GPU) has been employed to achieve high performance computing in seismic modeling and anisotropic RTM (e.g., Liu et al., 2012; Liu et al., 2013a; Liu et al., 2013b; Li et al., 2017).

This paper is organized as follows. First, the PWE in arbitrary OA media is introduced. Second, the solution of the eigenvalue equation for the PWE in frequency-wavenumber domain is decomposed into an EDO and an ESO. Then, a novel PAWE in time-space domain is proposed by combining these two ellipsoidal operators and then conveniently solved by the least-squares (LS)-based finite-difference method (FDM). Third, the 3D hybrid absorbing boundary condition (HABC) with some valid adjustments of velocity is developed for removing edge artificial reflections in anisotropic media. Moreover, we illustrate the specific graphic processing unit (GPU) implementation for 3D seismic modeling and RTM. Fourth, numerical modeling and RTM tests both in 3D homogeneous and complex anisotropic media are carried out for both the conventional and the new schemes. We also briefly describe the limitations and expectations of this work in the “Discussions” section. Finally, the conclusions are summarized based on these analyses and experiments.

2. Theory and methodology

2.1. Pseudo-acoustic wave equation in arbitrary OA media

Under the pseudo-acoustic approximation, the 3D PWE in VOA media can be symbolically expressed as (Zhang and Zhang, 2011)

$$\frac{\partial^2 \mathbf{u}}{\partial^2 t} = \mathbf{CGu}, \tag{1}$$

where, $\mathbf{u} = (u_x, u_y, u_z)^T$ denotes the particle displacement vector and u_x, u_y and u_z are three displacement components along the x, y and z directions, respectively. In Eq. (1), the diagonal matrix $\mathbf{G}$ is defined as

$$\mathbf{G} = \ diag\left(\frac{\partial^2}{\partial x^2}, \frac{\partial^2}{\partial y^2}, \frac{\partial^2}{\partial z^2}\right), \tag{2}$$

where, $\frac{\partial^2}{\partial x^2}$, $\frac{\partial^2}{\partial y^2}$ and $\frac{\partial^2}{\partial z^2}$ represent second-order derivatives along three spatial directions, respectively. In the acoustic case, the elastic constant matrix $\mathbf{C}$ can be determined by six Thomsen's anisotropy parameters (Tsvankin, 1997). Here, we rewrite $\mathbf{C} = v_{pz}^2\mathbf{N}$, and $\mathbf{N}$ is the parameter matrix for VOA media and has the following form

$$\mathbf{N} = \begin{bmatrix} 1+2\varepsilon_2 & (1+2\varepsilon_2)\sqrt{1+2\delta_3} & \sqrt{1+2\delta_2} \\ (1+2\varepsilon_2)\sqrt{1+2\delta_3} & 1+2\varepsilon_1 & \sqrt{1+2\delta_1} \\ \sqrt{1+2\delta_2} & \sqrt{1+2\delta_1} & 1 \end{bmatrix}. \tag{3}$$