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A robust absorbing layer method for anisotropic seismic wave modeling

L. Métivier[a,b,*], R. Brossier[b], S. Labbé[a], S. Operto[c], J. Virieux[b]

[a] LJK, CNRS, Université de Grenoble, BP 53, 38041 Grenoble Cedex 09, France
[b] ISTerre, Université de Grenoble I, BP 53, 38041 Grenoble Cedex 09, France
[c] Géoazur, Université de Nice Sophia-Antipolis, CNRS, IRD, OCA, Villefranche-sur-Mer, France

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ABSTRACT

When applied to wave propagation modeling in anisotropic media, Perfectly Matched Layers (PML) exhibit instabilities. Incoming waves are amplified instead of being absorbed. Overcoming this difficulty is crucial as in many seismic imaging applications, accounting accurately for the subsurface anisotropy is mandatory. In this study, we present the SMART layer method as an alternative to PML approach. This method is based on the decomposition of the wavefield into components propagating inward and outward the domain of interest. Only outgoing components are damped. We show that for elastic and acoustic wave propagation in Transverse Isotropic media, the SMART layer is unconditionally dissipative: no amplification of the wavefield is possible. The SMART layers are not perfectly matched, therefore less accurate than conventional PML. However, a reasonable increase of the layer size yields an accuracy similar to PML. Finally, we illustrate that the selective damping strategy on which is based the SMART method can prevent the generation of spurious S-waves by embedding the source in a small zone where only S-waves are damped.

1. Introduction

Accounting for the anisotropy of the subsurface in seismic wave propagation modeling is a crucial issue. At the exploration scale, in numerous environments, the subsurface does not satisfy the standard assumption of isotropic propagation. In sedimentary basins, for instance, the piling-up of small shale layers induce differences between horizontal and vertical wave velocities. Anisotropy is also observed near foothills environments, or in overthrust areas. With the current development of wide azimuth seismic acquisition systems, modern seismic imaging methods require robust modeling engines accounting accurately for the true Earth anisotropy. Indeed, these method rely on an accurate interpretation of the wave propagation, both in terms of kinematics and amplitude variations, two factors on which anisotropy can have a strong imprint.

The most natural way for accounting for anisotropy is to use an elastic description of the subsurface. In this case, the different types of anisotropy result in different expressions of the stiffness tensor which relates stress to strain components. The simplest types of anisotropy usually employed are Vertical Transverse Isotropy (VTI) or Horizontal Transverse Isotropy (HTI). In these two cases, the anisotropy symmetry axis is aligned with the vertical (VTI) or horizontal (HTI) axis. This

* Corresponding author.
E-mail address: ludovic.metivier@ujf-grenoble.fr (L. Métivier).
URL: http://www-ljk.imag.fr/membres/Ludovic.Metivier/ (L. Métivier).

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approximation is generalized to Tilted Transverse Isotropy (TTI) through the introduction of a tilt angle from the vertical axis defining the symmetry axis along with the anisotropy is aligned. More generic anisotropy description can also be considered: orthorombic anisotropy, or full (triclinic) anisotropy. In this latter case, the stiffness tensor associated with the 3D elastic dynamics is constituted of 21 independent parameters. In this study we will restrict to the simpler cases of VTI, HTI and TTI anisotropy. This three cases are also more generally referred to as Transverse Isotropy (TI).

The choice of an elastic wave propagation model may not be appropriate. First, in a modeling perspective, it is often difficult to obtain accurate estimation of parameters associated with the propagation of shear waves. Second, the computational cost associated with the solution of the corresponding system of equation is high. This is especially disadvantaging for seismic imaging methods such as Full Waveform Inversion [44] or Reverse Time Migration [22], which requires an important number of wave propagation problems to be solved at each step of the inversion. From the will to alleviate this computational burden originates the idea of designing acoustic anisotropic models [4]. Although these anisotropic acoustic models have no physical reality, the objective is to correctly describe the propagation of pressure waves (P-waves), while neglecting the propagation of shear waves (S-waves), under the assumption of weak-to-moderate anisotropy which characterizes geological media [42]. This approximation is also motivated by the observation that in numerous seismic exploration case studies, particularly in marine environment, the imprint of S-waves in the signal is weak and P-waves are dominant.

In practice, the acoustic anisotropic approximation is obtained by setting to 0 the S-wave velocity along the anisotropy symmetry axis, either from the dispersion relation associated with the linear elasticity equations, as initially proposed by Alkhalifah [3,4], and later on Zhou et al. [48], Operto et al. [38], or starting from an elastic description of the wave propagation, as promoted by Duveneck and Bakker [19].

Note that in general, the acoustic TI equations still include artificial S-wave modes. Indeed, even if the S-wave velocity is equal to zero along the anisotropy symmetry axis and directions perpendicular to this axis, its value may be non-zero in arbitrary directions [24]. For these equations, ad-hoc strategies have thus been designed to mitigate as much as possible the generation of spurious S-waves. We will see that the SMART layer method yields a complementary and efficient approach to overcome this difficulty.

For most of seismic modeling and imaging applications, the subsurface is considered as a semi-infinite medium. A free surface condition on top delineates the interface between the ground (or sea) and the air; the Earth is considered to extend infinitely in depth and lateral directions. However, the numerical domain in which the computation is performed is finite. It is therefore necessary to use Absorbing Boundary Conditions (ABC) or absorbing layers to avoid fictitious reflections.

First-order ABC (known also as radiation boundary conditions), introduced in the pioneering studies of Clayton and Engquist [14] and Engquist and Majda [21] are easy to implement for simple wave equations models, such as the acoustic wave equation. While these equations are exact in a mono-dimensional context (the outgoing waves are absorbed without introducing spurious reflections), this is not true for multi-dimensional problems. In particular, waves arriving to the boundary with grazing incidence generate spurious reflections. An improvement of these ABC can be achieved through the design of higher-order version [15,23]. If the accuracy of these ABC is improved, their implementation is more complex, as they imply the use of fractional high-order derivatives. In this case, the approximation of the differential operator at the boundary yields a complex system of equations to solve. In practice, it is difficult to guarantee the stability of such methods, and a correct absorption of waves at all incidence angles.

An alternative to absorbing boundary conditions consists in the design of absorbing layers: the domain of interest is surrounded with a layer where waves incoming from the domain of interest are artificially damped. This idea has first been promoted by Cerjan et al. [13] for the second-order in time acoustic equation. Despite this simple formalism, in practice, the design of such absorbing layer is difficult. Except for the 1D problem, the introduction of the layer generates reflections at the interface between the domain of interest and the layer. These reflections can be mitigated by choosing variable damping coefficient that smoothly grow from zero at the interface between the layer and the domain of interest, to the external boundary of the layer. However, this reduces the absorbing capability of the layer and requires to increase its size, which, in turn, increases the overall computational time of the simulation.

The Perfectly Matched Layers (PML) method, introduced by Bérenger [9], has become rapidly popular as it achieves an excellent trade-off between these two contradictory requirements. The initial method is based on a splitting of the hyperbolic system and the introduction of smooth damping coefficients in the layer. The PML strategy was originally designed for the 2D and 3D Maxwell's equation [9,10]. For these equations, a plane wave analysis demonstrates that the reflection coefficient at the interface between the domain of interest and the layer is null for wave propagating at all angles. In practice, the reflectivity for the discrete problem is not exactly zero, and when PML are used in heterogeneous models, a WKB analysis shows that only the leading order of the reflection coefficient is zero (see the review paper by Halpern et al. [25]). However, in many practical applications the amplitude of the spurious reflected waves remains very small.

Because of this remarkable property, the PML method is now the standard for the simulation of wave propagation in numerous applications. The method has been progressively extended to different wave propagation systems, from acoustic wave propagation, [39,17,11], to linearized Euler equations [28,27,2], and linear elasticity [26,16,6,31,5]. Later on, Convolutional PML (C-PML) [30,34,33] have been proposed to improve the absorption of wave propagating at grazing angles to the interface between the domain of interest and the layer. This method is based on a generalization of the complex-valued stretching related to the standard PML formulation in the frequency-domain.

However, when applied to the modeling of wave propagation in anisotropic media, the PML and C-PML methods become amplifying, which causes difficulties for their application to this particular case. This amplification has first been noted in