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A Hybrid Finite-Difference Approach to Acoustic-Elastic Wave Propagation in Marine Seismic Imaging

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Abstract Summary

This work presents a computational framework for simulating coupled acoustic-elastic wave propagation in marine seismic settings, with a focus on Full Waveform Inversion (FWI). The model uses a hybrid strategy: solving only for pressure in the seawater (acoustic layer) and for the full elastic wavefield in the seafloor (solid medium). Implemented in Devito, a domain-specific language for finite difference (FD) PDE modeling, this approach significantly reduces memory and computational demands while preserving accuracy at the fluid-solid interface. Benchmark tests validate the solver's performance and accuracy, highlighting its suitability for large-scale 3D marine FWI applications.

Introduction

Efficient and accurate simulation of wave propagation in heterogeneous media is a cornerstone of seismic imaging and inversion, particularly FWI. In marine settings, the geological model typically consists of an acoustic fluid layer (seawater) overlying an elastic solid medium (seafloor). This work focuses on the development of a computational framework for simulating coupled acoustic-elastic wave propagation using Devito (Luporini et al. (2018)), a high-level domain-specific language for finite difference modeling of partial differential equations. A key feature of this implementation is its hybrid modeling strategy, which solves only for pressure in the acoustic fluid layer and for the full elastic wavefield in the solid domain. This selective approach significantly reduces both memory usage and computational cost, without compromising physical accuracy at the fluid-solid boundary.

This report outlines the mathematical formulation of the coupled system, the memory-efficient hybrid discretization strategy, and implementation within Devito. Validation is performed through benchmark tests, demonstrating both accuracy and performance benefits. The developed solver represents a step forward in enabling cost-effective and physically consistent simulations for marine seismic imaging and inversion.

Methodology

The solver is implemented within the Devito framework, which allows for concise expression of coupled PDE systems and automatic generation of optimized low-level code, enabling scalable and portable simulations. We implemented the fluid-solid coupling using a Devito feature that allows us to define individual functions on particular subdomains of the simulation region. This strategy is inspired on the 'Defining Functions on Subdomains' tutorial at devitoproject.org. We start with the two sets of wave equations: The second-order constant-density acoustic wave equation in the fluid region (Shearer (2019)):

$$\ddot{p} - c_f^2 \nabla^2 p = f, \tag{1}$$

where we solve for the pressure field as a function of time and position, $p(t,\vec{r})$, and f is a source term. In the solid region, the first-order isotropic system in terms of velocity and stress tensor

$$\begin{cases} \rho_s \dot{v}_i &= \partial_j \tau_{ij}, \\ \dot{\tau}_{ij} &= \lambda \dot{\epsilon}_{kk}\delta_{ij} + 2\mu\dot{\epsilon}_{ij}, \end{cases} \tag{2}$$

where ϵ_{kk} and ϵ_{ij} are the trace of the strain tensor and the strain tensor, respectively. $v_i = v_i(t,\vec{r})$ are the components of the velocity field and $\tau_{ij} = \tau_{ij}(t,\vec{r})$ are the components of the stress tensor.

We divide the simulation domain into 6 logical Devito **Subdomains** as illustrated in Fig. 1. Eq. 1 is solved in the **Subdomain** *Upper*. The P.D.E for the velocity field is defined in the **Subdomain** *LowerField*, and finally, the P.D.E. for τ is defined in the **Subdomain** *Lower*. The **Subdomains** *UpperTransition* and *LowerTransition* are used to couple the acoustic and elastic wave equations as described below.

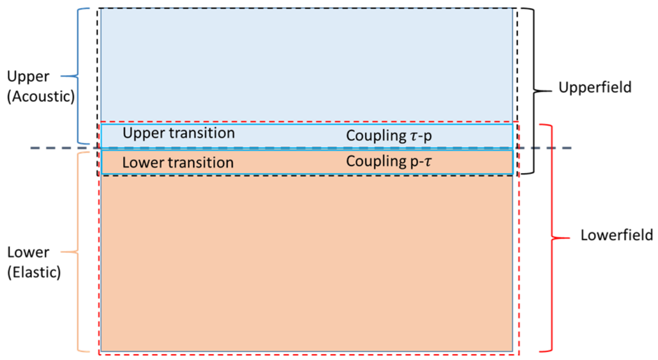


Figure 1: Simulation subdomains.

To effect the coupling between acoustic and elastic physics, we apply the following relationships in the transition zone formed by the *UpperTransition* and *LowerTransition* **Subdomains**: In the **Subdomain** *UpperTransition*, we couple the pressure with the diagonal components of stress as

$$\begin{cases} \tau_{xx} = p, \\ \tau_{yy} = p, \\ \tau_{zz} = p. \end{cases} \tag{3}$$

In the **Subdomain** *LowerTransition* we couple p and τ according to how the stress tensor reduces to in hydrostatic media:

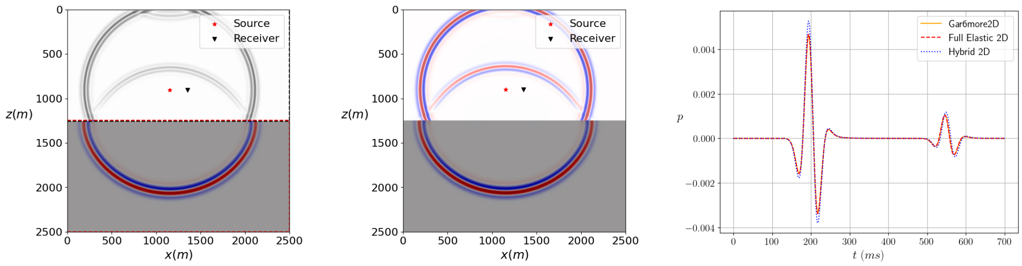
$$p = (\tau_{xx} + \tau_{yy} + \tau_{zz})/3 \tag{4}$$

and similarly for 2D.

Results

Seafloor as a plane horizontal interface (2D)

We define a physical space composed of an upper half as a fluid layer, where $c_f = 1500$ m/s and $\rho_f = 1025$ kg/m^3, and a lower half as a solid layer, defined by velocities $c_P = 2000$ m/s, $c_S = 1200$ m/s, and density $\rho_s = 2000$ kg/m^3. A source and a receiver are both positioned 350 m above the interface, with a 200 m offset. The source emits a Ricker pulse derivative with a central frequency of 15 Hz. We compare the results of the hybrid method with those obtained by solving the elastic wave equation in the entire physical space, setting $c_S = 0$ m/s (and using the respective c_P and ρ values) in what would be the fluid layer. We also compare these traces with an analytical solution from the Gar6more2D software (Diaz and Ezziani (2010)). The FD grids were of 2000×2000 points. We show (in Figure 2 (a) and (b)) snapshots of the fields at 700 ms of simulation time. Figure 2(c) shows the data recorded at the sensor location obtained by the finite difference codes and by an analytical solution using the code Gar6more2D.



(a) Hybrid (b) Full Elastic (c) Receiver

Figure 2: (a): Pressure field in the fluid subdomain (solving the acoustic wave equation) and in the solid subdomain (solving the elastic wave equation). (b) Pressure field obtained by solving the elastic wave equation in the entire domain. c) Receiver data from the three different methods. In solid yellow, analytical (Gar6more2D); dashed line, numerical (elastic in the entire domain); and dotted blue, numerical (hybrid fluid-solid separation approach).

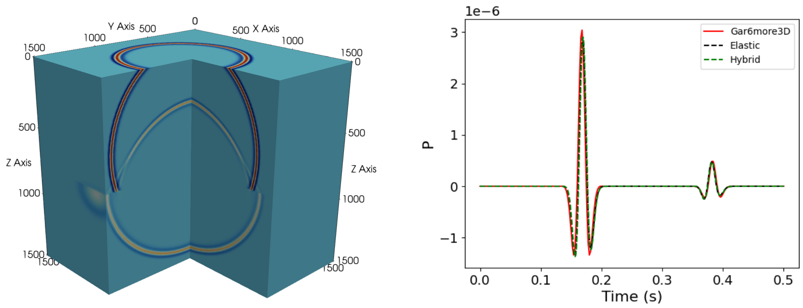
0.1 3D model

In this example, we demonstrate the gains in memory usage and kernel execution time achieved by using the hybrid approach. We created a two-layer 3D model with the top half being a fluid and the bottom half elastic, the physical properties are the same as in the 2D case. The FD grid has $301 \times 301 \times 301$ points, with a grid spacing of 5 m in each dimension. The source is a Ricker wavelet with a peak frequency of 30 Hz. The total memory usage and kernel execution time are shown in Table 1. The use of the hybrid approach reduced total memory usage by approximately 38% with a reduction in execution time of approximately 35.2% relative to solving the elastic equation in the entire domain.

Table 1: Computational cost

Implementation	RAM (MB)	Kernel execution Time (s)
Hybrid	1951	30.28
Elastic	3123	46.76

In order to assess the accuracy of the hybrid implementation, we compared the pressure field recorded at a receiver placed in the fluid layer. Figure 3(a) shows a 3D snapshot of the pressure field at 5 s, and 3(b) shows a comparison of the receiver data computed by Gar6more3D, elastic solver, and hybrid solver.



(a) Propagation at hybrid domain

(b) Receiver

Figure 3: (a): 3D Pressure field. c) Receiver data from the three different methods. In solid yellow, analytical (Gar6more3D); dashed line, numerical (elastic in the entire domain); and dotted blue, numerical (fluid-solid separation approach).

Conclusions

This work introduces an efficient and physically accurate computational framework for simulating coupled acoustic-elastic wave propagation in marine environments, tailored for seismic imaging and Full Waveform Inversion (FWI). By employing a hybrid modeling approach that solves only for pressure in the acoustic water layer and the full elastic wavefield in the solid seafloor, the method significantly reduces computational cost and memory usage without compromising the fidelity of wave interactions at the fluid-solid boundary. The implementation in Devito demonstrates flexibility and scalability, enabling realistic modeling in complex geological settings.

This work represents a meaningful step toward more accessible and efficient seismic inversion workflows, supporting broader adoption of advanced modeling techniques in marine geophysics. Future developments may include extension to anisotropic or viscoelastic media and integration into full inversion pipelines.

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