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Elastic Full-Waveform Inversion Using a Hybrid Misfit Function and Automatic Differentiation

Mesay Geletu Gebre (Federal University of Rio Grande do Norte), Paulo D. S. de. Lima (Federal University of Rio Grande do Norte), Claudionor G. Bezerra (Federal University of Rio Grande do Norte), João Medeiros Araújo (Universidade Federal do Rio Grande do Norte)

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Introduction

Elastic Full-Waveform Inversion (EFWI) is a powerful data-fitting technique that iteratively updates an initial subsurface model by minimizing the misfit between observed and simulated seismic data. The success of EFWI critically depends on the choice of the misfit function, as it directly influences the accuracy and robustness of the inversion process. The conventional least-squares (L_2-norm) misfit function is highly sensitive to outliers and often yields overly smooth models. To address this limitation, we propose a hybrid misfit function that iteratively combines the L_2 and L_1 norms. This formulation enhances the robustness, resolution, and flexibility of the inversion process.

Method

This work presents an Elastic Full-Waveform Inversion (EFWI) framework that incorporates a hybrid misfit function. The proposed multi-parameter EFWI method iteratively minimizes the hybrid objective function: $\Phi_H(\mathbf{m}) = w(i) \cdot \Phi_{L1}(\mathbf{m}) + (1 - w(i)) \cdot \Phi_{L2}(\mathbf{m})$, where $\Phi_{L1}(\mathbf{m})$ and $\Phi_{L2}(\mathbf{m})$ are the L_1 and L_2 norm-based misfit functions, respectively, $\mathbf{m}$ is the model parameter vector, and $w(i)$ is a weight function that varies with iteration i. We define the weight function using a sigmoid form: $w(i) = \frac{1}{1+\exp\left(-\left(i-\frac{N}{2}\right)\right)}$, where N is the total number of iterations. This sigmoid-based weighting enables dynamic adjustment of the hybrid misfit function throughout the optimization process. Initially, a higher weight is assigned to the L_2 norm to emphasize the recovery of low-wavenumber components. As iterations progress, the weight of the L_1 norm increases, enhancing the recovery of high-wavenumber details. We use a staggered-grid finite-difference scheme to solve the elastic wave equations for forward modeling. The inversion employs gradient-based optimization, with gradients of the hybrid misfit function computed using Automatic Differentiation (AD) for accuracy and computational efficiency. We employ the Adam algorithm to iteratively update the velocity model.

Results and Conclusions

We conducted numerical tests using both noise-free and noise-contaminated datasets derived from realistic velocity models to assess the practicality and robustness of the proposed approach. During the inversion, P-wave and S-wave velocities were updated simultaneously while keeping the density constant. The preliminary results suggest that the AD-driven EFWI method, incorporating a hybrid misfit function, provides improved resolution and a reliable reconstruction of geological structures. Standard evaluation metrics (RMSE and SSIM) indicate enhanced accuracy of the inverted models relative to the true ones. These findings highlight the method's robustness to noise and its ability to preserve structural details. Detailed tests and comparisons with conventional L_2-norm based methods will be presented during the presentation.