Finite-difference frequency-domain modeling of visco-acoustic wave propagation with a reflectionless discrete perfectly matched layer

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This paper was prepared for presentation during the 18th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 16-19 October, 2023.
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Abstract

Seismic wavefield simulations usually require truncating an otherwise infinite physical domain by the addition of an artificial computational boundary. The resulting computational domain needs to be as small as possible in order to keep computation time and memory usage within feasible bounds. On the other hand, the imposition of this artificial boundary creates unwanted reflections that propagate back to the interior of the region of interest, creating artifacts that must be eliminated. There are many published methods that aim at eliminating these boundary-spurious reflections. The Perfectly Matched Layer (PML) type methods are among the most effective and commonly used ones. Recently a very effective variation of the PML method, called the reflectionless discrete PML (D-PML), has been applied to the solution of seismic wavefield simulations. The D-PML method is developed by working in a discretized setting from the beginning in contrast to classical PML implementations that first develop the theory in a continuous setting to later apply it to a discretized domain. This strategy of discretizing first, in the D-PML, makes it completely free of reflections caused by the discretization of the domain, in contrast to the classical PML which still generates spurious reflections due to the approximation of the continuous problem by a discretized one. The D-PML adds two artificial fields that must be computed together with the physical wavefield which is the solution of the original wave equation. The addition of these two new fields immediately raises the question of the computational cost of this method and how to implement it efficiently. This computational aspect of the method is particularly important in the frequency domain where the partial differential equations involved give rise to a relatively big, although sparse, linear system of algebraic equations. In this work, we investigate the effectiveness of eliminating spurious boundary reflections and also the computational cost of using the D-PML for modeling the visco-acoustic wave equation in the frequency domain with the use of a direct solver (MUMPS). To our knowledge, this is the first time that the D-PML is implemented as an absorbing boundary condition for the seismic wave modeling in the frequency domain. We have conducted numerical simulations of typical 2D land and marine seismic surveys. We compared the performance of the D-PML against a classical PML based on a complex coordinate stretching that doesn't make use of additional auxiliary fields. Compared to a classical PML, we have verified that the D-PML requires thinner PML layers, doesn't require any progressive 'turning on' of the PML damping coefficient, and has a very strong attenuation of the field just a few nodes into the PML region. Regarding the computational cost, the additional auxiliary fields are only required to be supported on the PML regions in the model which, as already said, can be constructed with a minimum number of extra grid nodes. Also, the discretized auxiliary field equations have a very localized structure, which contributes to maintaining the sparsity of the system matrix meaning that the computational cost for its solution is only slightly increased.