Geophysical Research Abstracts, Vol. 7, 03115, 2005
SRef-ID: 1607-7962/gra/EGU05-A-03115

Finite boundary perturbation theory for the elastic equation of motion

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The crust is the most heterogeneous region of the Earth, and accurate crustal correction (i.e., accurate computation of the perturbation of synthetic seismograms caused by the crustal heterogeneities) is critical for obtaining accurate mantle structure models. The heterogeneities are usually represented by the summation of (i) the perturbation of physical properties (such as density and elastic constants) in the internal regions and (ii) the perturbation of the location of the boundaries (such as Moho and the surface), and the principal difficulty is how to compute the effect of the latter perturbation (e.g., Dahlen & Tromp 1998).

One popular solution is to use local trial functions. For example, the Finite Element Method in terms of local trial functions (e.g., Lysmer & Drake 1972) and the Spectrum Element Method (e.g., Priolo et al. 1994; Komatitsch & Vilotte 1998) can compute such effect in a straightforward manner. Mizutani (2001) proposed an optimally accurate Finite Difference Scheme (Geller & Takeuchi 1998; Takeuchi & Geller 2000) for the medium with arbitrary boundary shapes. Although forward computations up to higher frequencies for 3-D heterogeneous global Earth structure models has recently become feasible (e.g., Komatitsch & Tromp 2002ab; Tsuboi *et al*. 2003), the required CPU time is intensive and the applications such methods to global waveform inversion studies are still in the stage of becoming feasible.

The computational method applied to the actual waveform inversion studies for global 3-D Earth structure thus far has been either the modal summation method (e.g., Woodhouse & Dziewonski 1984; Li & Tanimoto 1993) or the Direct Solution Method (e.g., Hara *et al*. 1993; Geller & Ohminato 1994; Geller & Takeuchi 1995; Cummins *et al*. 1994; Takeuchi *et al*. 1996; Cummins *et al*. 1997). Both methods solve the weak form equation of motion (or its equivalence) and use vector spherical harmonics as the laterally dependent part of the trial functions. If the structure model has only large scale lateral heterogeneities, most of matrix elements become zero because of the 'selection rule,' and, thus, the required CPU time to solve the equation of motion is greatly reduced.

However, for those global trial functions, severe limitations still exist in computing the perturbation of synthetic seismograms caused by the perturbation in the location of the boundaries, because previous solutions rely on the first order perturbation theory of the free oscillation; Woodhouse (1976) and Woodhouse & Dahlen (1978) formulated a method to compute the perturbation of the eigenfrequencies, and Woodhouse (1980) extends these results to compute the perturbation of synthetic seismograms. They consider the infinitesimal perturbation of free oscillations in the vicinity of the 'reference frequency': representative eigenfrequency of the considered modes. Thus, this method breaks down for strongly heterogeneous medium or for higher frequencies.

In this study, we derive the exact weak form equation of motion for the medium with finite boundary perturbations. This method can be applied to arbitrary trial functions; that is, to both global and local trial functions. We can solve the derived equation of motion by either direct solution or higher order perturbation approximations, which allows highly accurate synthetic seismograms. We also show that we can derive the previous results by Woodhouse (1980) as a 'special case' of our formulation.