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# 3-D frequency-domain seismic wave modelling in heterogeneous, anisotropic media using a Gaussian Quadrature Grid (GQG) approach

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We have developed a modified version of the spectral element method (SEM), called the Gaussian Quadrature Grid (GQG) approach, for frequency domain 3D seismic modelling in arbitrary heterogeneous, anisotropic media. The model may incorporate an arbitrary free-surface topography and irregular subsurface interfaces. Unlike the SEM ,it does not require a powerful mesh generator such as the Delauney Triangular or TetGen. Rather, the GQG approach replaces the element mesh with Gaussian quadrature abscissae to directly sample the physical properties of the model parameters and compute the weighted residual or variational integral. This renders the model discretisation simple and easily matched to the model topography, as well as direct control of the model paramterisation for subsequent inversion. In addition, it offers high accuracy in numerical modelling provided that an appropriate density of the Gaussian quadrature abscissae is employed. The second innovation of the GQG is the incorporation of a new implementation of perfectly matched layers to suppress artificial reflections from the domain margins. We employ PML model parameters (specified complex valued density and elastic moduli) rather than explicitly solving the governing wave equation with a complex co-ordinate system as in conventional approaches. Such an implementation is simple, general, effective and easily extendable to any class of anisotropy and other numerical modelling methods.

The accuracy of the GQG approach is controlled by the number of Gaussian quadrature points per minimum wavelength, the so-called sampling density. The optimal sampling density should be the one which enables high definition of geological characteristics and high precision of the variational integral evaluation and spatial differentiation. Our experiments show that satisfactory results can be obtained using sampling densities of 5 points per minimum wavelength.

Efficiency of the GQG approach mainly depends on the linear-system solver of a large dimensional, sparse and symmetric complex matrix. The compressed half-row storage scheme is the one requiring the least computer memory, but with such an optimal storage scheme, the sequential, iterative Krylov solvers are still expensive in computer time due to their slow convergence. Therefore it is crucial to improve the computational efficiency of the GQG approach by developing a parallelised, iterative preconditioned Krylov solver in the future.

The GQG approach can be readily employed as the forward modelling component to yield synthetic spectral data in generalised diffraction tomography and in frequency-domain full waveform inversion. It can also be used with the adjoint method to compute the waveform sensitivity kernels for specified configurations of source-receiver pairs in arbitrary 3D anisotropic media. The accuracy and capabilities of the GQG modelling method are illustrated here by presenting all independent components of the Green's function vectors from directional sources in both homogeneous and heterogeneous, anisotropic media.