Finite Volume Analysis of LWD Electromagnetic Tool Response in Complex Borehole Environments Using Scalar and Vector Potentials

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The modeling of logging-while-drilling (LWD) tool response in three dimensional (3-D) complex earth formations, considering all important details of the tool geometry, constitutes a very challenging problem. A flexible numerical approach that is able to handle arbitrary geometries and media present in realistic borehole environments is the finite volume method (FVM). However, the presence of large resistivity contrasts in many earth formations is a major challenge for FVM. This is because in this case the solution process is plagued by ill-conditioning and convergence problems. To circumvent these issues, Maxwell's equations are reformulated here in terms of potentials in the null space of the curl operator and its complement by applying a Hodge-Helmholtz decomposition to the electric field. The null space of the curl operator is then eliminated by adding a stabilizing term using a Coulomb gauge condition.

In the FVM, the physical space is decomposed into small volumes and the partial differential equations are integrated over each volume. The proposed numerical scheme is based on a nonuniform 3-D staggered-grid developed in cylindrical coordinates to better conform to the majority of well-logging tool geometries and to avoid staircasing errors. The computational grid is uniform in the longitudinal z-direction and nonuniform in the radial ρ-direction. The cell size is increased in a smooth manner from the inner cell toward the outer cells to avoiding spurious numerical reflections in the grid. In order to simulate unbounded domain problems, a cylindrical complex-frequency-shifted perfectly matched layer (CFS-PML) is incorporated in the FVM computational grid. The formulation of CFS-PML is based on the complex coordinate stretching approach. By using CFS-PML, the 3-D finite volume grid can be made more compact in both the radial and axial directions, thus reducing the overall memory requirements for a given physical size. The FVM discretization yields a large non-Hermitian sparse linear system that is solved by preconditioned Krylov-subspace methods. We employ and compare both biconjugate gradient stabilized (Bi-CGSTAB) and restarted generalized minimal residual (RGMRES) as iterative solvers. The present FVM technique is validated against numerical mode matching (NMM) results, showing very good agreement.