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A Fast Multi-Scale Finite Element Method for Geophysical Resistivity Measurements

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Abstract : Logging-While Drilling (LWD) is a technique to record down-hole logging measurements while drilling the well. Nowadays, LWD devices (e.g., nuclear, sonic, resistivity) are mostly used commercially for geo-steering applications. Modern borehole resistivity tools are able to measure all components of the magnetic field by incorporating tilted coils. The depth of investigation of LWD tools is limited compared to the thickness of the geological layers. Thus, it is a common practice to approximate the Earth's subsurface with a sequence of 1D models. For a 1D model, we can reduce the dimensionality of the problem using a Hankel transform. We can solve the resulting system of ordinary differential equations (ODEs) either (a) analytically, which results in a so-called semi-analytic method after performing a numerical inverse Hankel transform, or (b) numerically. Semi-analytic methods are used by the industry due to their high performance. However, they have major limitations, namely: -The analytical solution of the aforementioned system of ODEs exists only for piecewise constant resistivity distributions. For arbitrary resistivity distributions, the solution of the system of ODEs is unknown by today's knowledge. -In geo-steering, we need to solve inverse problems with respect to the inversion variables (e.g., the constant resistivity value of each layer and bed boundary positions) using a gradient-based inversion method. Thus, we need to compute the corresponding derivatives. However, the analytical derivatives of cross-bedded formation and the analytical derivatives with respect to the bed boundary positions have not been published to the best of our knowledge. The main contribution of this work is to overcome the aforementioned limitations of semi-analytic methods by solving each 1D model (associated with each Hankel mode) using an efficient multi-scale finite element method. The main idea is to divide our computations into two parts: (a) offline computations, which are independent of the tool positions and we precompute only once and use them for all logging positions, and (b) online computations, which depend upon the logging position. With the above method, (a) we can consider arbitrary resistivity distributions along the 1D model, and (b) we can easily and rapidly compute the derivatives with respect to any inversion variable at a negligible additional cost by using an adjoint state formulation. Although the proposed method is slower than semi-analytic methods, its computational efficiency is still high. In the presentation, we shall derive the mathematical variational formulation, describe the proposed multi-scale finite element method, and verify the accuracy and efficiency of our method by performing a wide range of numerical experiments and comparing the numerical solutions to semi-analytic ones when the latest are available.

Keywords : logging-While-Drilling, resistivity measurements, multi-scale finite elements, Hankel transform
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