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Improving seismic interpretation: a high-contrast approximation to the reflection coefficient of a plane longitudinal wave

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Abstract: Linearized approximations of reflection and transmission coefficients set a foundation for amplitude versus offset (AVO) analysis and inversion in exploration geophysics. However, the weak properties contrast hypothesis of those linearized approximate equations leads to big errors when the two media across the interface vary dramatically. To extend the application of AVO analysis and inversion to high contrast between the properties of the two layers, we derive a novel nonlinearized high-contrast approximation of the PP-wave reflection coefficient, which establishes the direct relationship between PP-wave reflection coefficient and P-wave velocities, S-wave velocities and densities across the interface. (A PP wave is a reflected compressional wave from an incident compressional wave (P-wave).) This novel approximation is derived from the exact reflection coefficient equation with Taylor expansion for the incident angle. Model tests demonstrate that, compared with the reflection coefficients of the linearized approximations, the reflection coefficients of the novel nonlinearized approximate equation agree with those of the exact PP equation better for a high contrast interface with a moderate incident angle. Furthermore, we introduce a nonlinear direct inversion method utilizing the novel reflection coefficient equation as forward solver, to implement the direct inversion for the six parameters including P-wave velocities, S-wave velocities, and densities in the upper and lower layers across the interface. This nonlinear inversion algorithm is able to estimate the inverse of the nonlinear function in terms of model parameters directly rather than in a conventional optimization way. Three examples verified the feasibility and suitability of this novel approximation for a high contrast interface, and we still could estimate the six parameters across the interface reasonably when the parameters in both media across the interface vary about 50%.

Key words: High-contrast interface, reflection coefficient, amplitude variation with angle, multi-parameter estimation, artificial neural network inversion

1 Introduction

The Zoeppritz equation (Zoeppritz and Erdbebnenwellen, 1919) and its approximations as the fundamental mathematical formulae for describing the amplitudes of PP reflected waves from P-wave incident plane waves in exploration geophysics under plane wave approximation play an important role in AVO analysis/inversion (Smith and Gidlow, 1987; Buland and Omre, 2003; Downton and Lines, 2004; Yin et al, 2008; Zhang et al, 2012; Zong et al, 2012a; Zhang et al, 2013), lithology prediction (Ursin et al, 2003; Fu et al, 2005; Buland et al, 2008; Ulvmoen and Omre, 2010; Ulvmoen et al, 2010; Rimstad et al, 2012) and fluid discrimination (Zhang et al, 2010; Russell et al, 2011; Rimstad et al, 2012; Wang et al, 2012; Zong et al, 2012b). The Zoeppritz equation gives the precise values of the amplitudes of the PP reflected plane wave. However, its intrinsic nonlinearity makes it less appropriate in practical applications. Therefore, linearized approximations with different parameterization of the Zoeppritz equations are more popular and practical (Bortfeld, 1961; Shuey, 1985; Lu and McMechan, 2004; Vedanti and Sen, 2009; Karimi et al, 2010; Alemie and Sacchi, 2011; Kim et al, 2011; Zhu and McMechan, 2012; Zong et al, 2012b). For details about different types of linearized approximations see Russell et al (2011). The linearized approximations are derived under the hypothesis of weak property contrasts between layers or limited incident angle. However, these assumptions do not hold especially at unconformities or at interfaces between different lithofacies (Ayzenberg et al, 2009; Skopintseva et al, 2011). Therefore, in this paper, we attempt to derive an approximation of the PP reflection coefficient to adjust to

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