2-D Frequency-domain Waveform Inversion of Coupled Acoustic-Elastic Media with an Irregular Interface

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Abstract—In order to correctly interpret marine exploration data, which contain many elastic signals such as S waves, surface waves and converted waves, we have developed both a frequency-domain modeling algorithm for acoustic-elastic coupled media with an irregular interface, and the corresponding waveform inversion algorithm. By applying the continuity condition between acoustic (fluid) and elastic (solid) media, wave propagation can be properly simulated throughout the coupled domain. The arbitrary interface is represented by tessellating square and triangular finite elements. Although the resulting complex impedance matrix generated by finite element methods for the acoustic-elastic coupled wave equation is asymmetric, we can exploit the usual back-propagation algorithm used in the frequency domain through modern sparse matrix technology. By running numerical experiments on a synthetic model, we demonstrate that our inversion algorithm can successfully recover P- and S-wave velocity and density models from marine exploration data (pressure data only).

Key words: Waveform inversion, frequency-domain, acoustic-elastic coupled media, finite-element method.

1. Introduction

For thirty-five years, geophysicists have attempted to find a way to determine subsurface properties of the earth and illuminate the subsurface structure via waveform inversion. Geophysicists have developed waveform inversion in two different directions. One involves direct methods and the other employs indirect methods based on classical optimization techniques such as the gradient, Gauss-Newton and full Newton method (PRATT et al., 1998). The direct inversion method aims to find material properties of the earth by applying the basic but mathematically elegant seismic imaging concept (CLAERBOUT, 1971; KEYS and WEGLEIN, 1983; WEGLEIN et al., 2003). On the other hand, the indirect inversion method tries to determine the subsurface velocity model by minimizing the objective function, usually defined by the $l_2$ norm between the measured and modeled data.
(Pratt et al., 1998; Shin and Min, 2006). From the viewpoint of exploration seismologists, waveform inversion is one of the most attractive and fascinating techniques being explored, since it does not require human interpretation and can lead to quantitative visualization of the earth’s structure with high resolution. Since Lailly (1983) and Tarantola (1984) suggested the back-propagation algorithm for calculating the gradient direction efficiently, extensive studies based on their ideas have been conducted on waveform inversions. However, several obstacles such as (1) improper initial model, (2) inadequate model type that produces an unrealistic set of the earth’s parameters, (3) absence of low frequency components in field data, and (4) local minima or non-uniqueness problems of a nonlinear objective function, have made applications of waveform inversion to field data unsuccessful. In spite of these disadvantages, waveform inversion still remains a promising technique for the geophysics community.

In this study, we concentrate our attention on frequency-domain waveform inversion, especially in marine environments with an irregular sea floor. Wave propagation in the marine environment is always associated with two media; the sea is an acoustic layer in which only P waves propagate, and the earth is an elastic layer in which both P waves and S waves propagate. Since geophysicists have not developed an elegant technique to handle marine seismic data by considering acoustic-elastic coupled media, seismic data from marine exploration (pressure or 4-component OBC data) are usually processed by assuming that the data obey the acoustic wave equation. This assumption leads to a reduction in computational cost and simpler algorithms. However, in order to interpret marine exploration data correctly, we need to develop inversion algorithms based on the acoustic-elastic coupled wave equation, which can treat wave propagation properly throughout acoustic-elastic coupled media. To represent wave propagation correctly, acoustic-elastic coupled media should satisfy the continuity condition at the interface; the pressure of the acoustic layer is equal to the composite normal stress of the horizontal and vertical elastic force.

Recently, Choi et al. (2008) developed frequency-domain modeling and an inversion algorithm for acoustic-elastic coupled media, where the fluid-solid interface is flat. However, since the actual sea floor is generally irregular, it is essential to consider this aspect when implementing acoustic-elastic coupled waveform inversion in the marine environment. In this paper, we develop frequency-domain modeling and a waveform inversion algorithm for acoustic-elastic coupled media which can deal with an irregular sea floor. This enables us to successfully recover the elastic parameters such as P-wave velocity, S-wave velocity and density from pressure data alone, collected in the marine seismic survey. The wave propagation of acoustic-elastic coupled media with an irregular interface can be implemented in frequency-domain modeling using the finite-element method (FEM). To represent an irregular fluid-solid interface, both perfect square and isosceles triangle elements are used. The gradient direction of the objective function defined by the $l_2$ norm between the measured and modeled data is efficiently calculated by exploiting a common back-propagation algorithm, a technique which has been extensively exploited in waveform inversion (Tarantola, 1984; Pratt et al., 1998; Shin