Reducing crosstalk in viscoelastic FWI through parameterization choice

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Summary

Useful information about seismic amplitudes is often underused in full waveform inversion due to the common neglect of elastic or attenuative physics. Viscoelastic full waveform inversion allows for better use to be made of measured data. Inter-parameter cross-talk is a major concern in this problem, particularly due to confusion between velocity and Q effects in the data. We propose a strategy for cross-talk mitigation based on prioritizing the transmissive effects of the Q variables. This strategy allows for cross-talk arising from data residuals in the reflections to be reduced.

Introduction

In concept, full waveform inversion (FWI) attempts to find the subsurface model best describing the full information content of a seismic experiment (Tarantola, 1984). While this ambitious goal is far from being realized, FWI approaches have proved to be effective tools for the recovery of intermediate scale P-wave velocity models. The FWI strategy in this context, while highly successful, relies heavily on a constant-density, acoustic model of wave propagation. This means that inversion results are mostly restricted to explaining the phase information of P-wave arrivals contained in measured data, falling well short of the conceptual promise of the technique. Significant efforts are being made to make more complete formulations of FWI more practical.

Important sources of information in seismic data are neglected in acoustic FWI approaches, significantly amplitudes. Amplitude information has been employed with great success in exploration geophysics in the analysis of amplitude variation with offset (AVO) to better understand the elastic properties of the subsurface. In order to reproduce accurate AVO effects it is necessary to consider an elastic model of wave propagation. While elastic formulations of FWI were proposed shortly after the original acoustic algorithm (Tarantola, 1986), most progress which has been made in FWI has centered on the constant density acoustic case. This is partly due to the considerable computational cost of modeling elastic wave propagation, but also to the difficulty of correctly treating amplitude information in FWI Virieux and Operto (2009). Seismic waves are considerably attenuated in the subsurface, and if this is not considered in the inversion, FWI may still struggle to correctly interpret amplitude information.

Despite the major role attenuation plays in seismic wave propagation, it is often neglected in elastic FWI formulations. While the treatment of attenuation as characterized by Q in FWI has been studied, most research has been done in a viscoacoustic setting (e.g., Hicks and Pratt, 2001; Malinowski et al., 2011; Kamei and Pratt, 2013; Métivier et al., 2015; Plessix et al., 2016; Keating and Innanen, 2016, 2017). These approaches have shown success but suffer from the same neglect of elastic information as the constant density acoustic algorithm. The viscoelastic FWI problem, in which both elastic properties and Q are considered, is investigated less frequently but has a greater potential to accurately reproduce seismic wave propagation.

There are many challenges associated with moving from constant density acoustic FWI to viscoelastic FWI. One major concern is inter-parameter cross-talk, where different physical properties are confused with one another in the inversion. Here, we suggest a strategy for reducing cross-talk in visco-elastic full waveform inversion by altering the spatial extent of the variables considered.

Theory

Cross-talk is the phenomenon in which the data signatures of different physical properties are confused in FWI. The challenges associated with cross-talk are a major obstacle to the effective implementation of multiparameter FWI. Cross-talk is typically caused in one of two ways. If the data measured do not adequately constrain the possible subsurface models, then cross-talk can arise as the result of genuine ambiguity. Typically, a 3C seismic survey provides significant information that this type of uncertainty has a relatively minor contribution to cross-talk for the viscoelastic problem.

Cross-talk can also be caused by the iterative nature of the FWI procedure. In FWI, data residuals (the difference between the measured data and the synthetic data generated from the current model) cannot be eliminated in a single step, and so are gradually reduced in a series of iterations. Because a reduction in the data residual requires that the measured data be only partially predicted, this means that an incorrect model variable may be changed to describe part of a data residual caused by another. Variables with similar data footprint are particularly prone to this type of cross-talk, as they are better able to describe data residuals not caused by errors in those variables.

While cross-talk is a concern in all multi-parameter FWI implementations, the viscoelastic problem is particularly prone to cross-talk. This is partially caused by the large number of parameters which can be confused but is further compounded by the similar data signature of the Q and velocity variables. Because Q effectively introduces an imaginary term to the velocity (via attenuation) and shifts the real part (via dispersion), changes in Q alter measured data in a way very similar to changes in velocity. This makes these variables easy to confuse.

When model variables are well constrained by data, no data residual caused by one viscoelastic parameter can be completely recreated by a combination of others. This means that the ability of wrong variables to describe data residuals decreases with the residuals. Inversion approaches which take this behaviour into account are better able to avoid cross-talk. These approaches are typically based on Newton optimization, which can be very effective but is also computationally intensive to implement. In practice, the Newton update is usually only approximated in FWI, and so it is still very beneficial to choose inversion variables which suffer relatively little cross-talk with one another.

One way to reduce the substantial cross-talk between velocity and Q is to redefine the FWI problem with respect to variables less prone to cross talk. In particular, cross-talk with Q variables introduced by reflections in the data can be avoided. This type of cross-talk can be introduced when reflections caused by changes in elastic properties are mistakenly attributed to Q contrasts instead. While reflections can be introduced by contrasts in Q (Lines and Vasheghani, 2008), this effect is usually minor, and the effects of attenuation are typically much more significant in seismic exploration. If it is assumed that reflections from Q contrasts are negligible in the measured data, it is possible choose a set of variables parameterizing the Q model which are incapable of introducing reflections. An example of this type of variable is shown in figure 1. As these variables describe a long wavelength change in the model, their capacity to introduce reflections is very small. These variables can help to reduce cross-talk from reflection-type features in the data. The large spatial size of these variables means that relatively few of them should be sufficient to describe the model. This also means that the dimensionality of the optimization problem can be reduced, allowing for the computational cost of the problem to be reduced.

Examples

The response of seismic waves to changes in the inversion variables can be studied through the use of radiation patterns. These are measures of how small perturbations in a given parameter change the wavefield. Study of radiation patterns can reveal which data are sensitive to which variables. Figure 2 shows the real part of the radiation patterns of perturbations of different visco-elastic parameters for frequency domain data at 15Hz. The source position is marked with a red star, and the model is perturbed at the green dot. In conventional FWI, variables are defined which describe parameter values at each finite-difference grid cell in the model. The radiation patterns associated with v_P and Q_P variables of this type are shown in the left and center of Figure 2, respectively. The radiation patterns are highly similar at all scattering angles, making these variables very difficult to distinguish from one another, and so prone to cross-talk. The radiation pattern associated with a spatially distributed Q_P variable is shown on the right of Figure 2. While there is still significant similarity to the v_P pattern at transmissive scattering angles, this radiation pattern does not introduce reflections, which allows for reflection-based cross-talk to be eliminated.

Conclusions

Visco-elastic full waveform inversion introduces several complications to the FWI problem, cross-talk significantly among them. Cross-talk is especially severe between velocity and Q variables. The strategy of using long wavelength variables for Q characterization offers the potential to reduce reflection-based cross-talk into Q variables in visco-elastic FWI.

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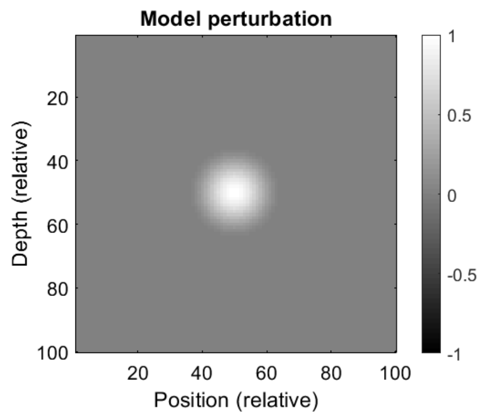

Figure 1. Spatial distribution of low cross-talk Q variables. The lack of high frequencies prevents variables like these from introducing reflections.

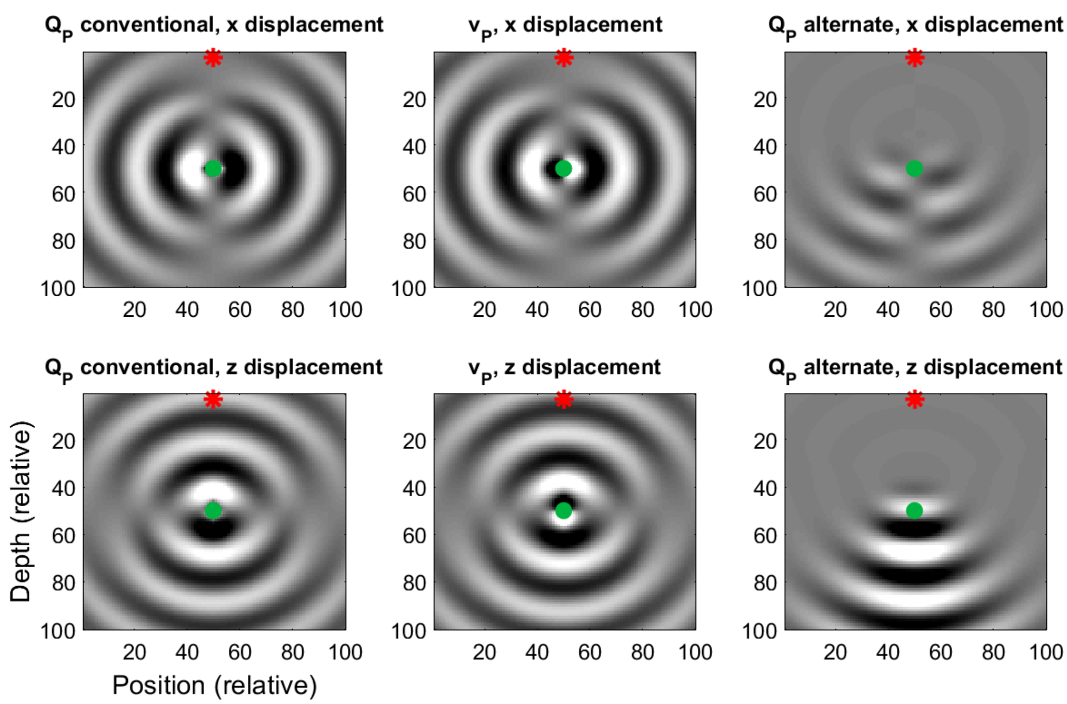

Figure 2. Real part of numerical radiation patterns for a conventional point-like Q_P variable (left), a conventional v_P variable (center), and the proposed Q_P variable (right). Source position is denoted by the red star, and the perturbations are centered at the green circle.

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