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**3D elastic full waveform inversion using P-wave excitation
amplitude: Application to OBC field data**

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Abstract

We propose an efficient elastic full waveform inversion (FWI) based on the P-wave excitation amplitude (maximum energy arrival) approximation in the source wavefields. Because, based on the P-wave excitation approximation (ExA), the gradient direction is approximated by the cross-correlation of source and receiver wavefields at only excitation time, it estimates the gradient direction faster than its conventional counterpart. In addition to this computational speedup, the P-wave excitation approximation automatically ignores SP and SS correlations in the approximated gradient direction. In elastic FWI for ocean bottom cable (OBC) data, the descent direction for the S-wave velocity is often degraded by undesired long-wavelength features from the SS correlation. For this reason, the P-wave excitation approach increases the convergence rate of multi-parameter FWI compared to the conventional approach. The modified 2D Marmousi model with OBC acquisition is used to verify the differences between the conventional method and ExA. Finally, the feasibility of the proposed method is demonstrated on a real OBC data from North Sea.

Keywords: Full waveform inversion, 3D elastic inversion, Excitation amplitude, Mode separation, Anisotropy

Introduction

Although seismic full-waveform inversion (FWI) aims at high-resolution recovery of the unknown sub-surface parameters from the seismic data (Tarantola, 1984; Gauthier et al., 1986; Pratt, 1990; Pratt et al., 1998), it is a computationally cumbersome process, requiring a long-time and large memory space/disk storage. Moreover, the computational cost increases as we alleviate the endemic problem of non-linearity associated with FWI (Symes 2008; van Leeuwen and Herrmann, 2013; Biondi and Almomin, 2014; Alkhalifah, 2015; Alkhalifah and Wu, 2016). Also, there is a general tradeoff between incorporating better (more accurate) physics in the inversion framework (e.g. elasticity, anisotropy, etc.) and the computational cost (Operto et al., 2013; Warner et al., 2013; Oh and Alkhalifah, 2016).

FWI is an iterative process of updating the model parameters using the gradient of a misfit function between the observed and simulated seismic data (Gauthier et al., 1986; Tarantola, 2005). Thanks to the adjoint state method, computing the huge Jacobian matrix (Lailly, 1983; Plessix, 2006) is not required. Instead, the gradient computation requires both the source and adjoint wavefields to be available for a dot product operation. However, it ends up involving redundant floating-point operations (FLOPs). Since FWI seeks to capture the fine-scale details of the earth model, it requires a fine numerical grid in the model. As a consequence of Courant-Friedriches-Lewy (CFL) condition, the fine spatial grid imposes even finer time sampling. In addition, the low velocity of the shear waves in multi-parameter elastic inversion, which is much slower than the P wave velocity, requires even finer grid (Tarantola, 1986; Brossier et al., 2009; Köhn et al., 2012; Prieux et al., 2013; Vigh et al., 2014). Concurrently, the advancements in the acquisition such as multi-component, wide azimuth and so on, are cultivating huge datasets (of the order of terabytes in size) so as to

improve the inversion results.

Although we are experiencing progress in general in the cost category of FWI, the above-discussed factors still pose computational challenges for FWI, especially in large 3D problems (Virieux and Operto, 2009). Over the years, numerous solutions have been proposed to mitigate those challenges. For example, the choice of the optimization scheme usually effects the number of iterations needed to reach a convergent model (Pratt et al. 1998; Nocedal and Wright, 2006; Ma and Hale, 2012; Métivier et al., 2014). In this paper, we focus on the reduction of computational cost within each iteration during the process of computing the gradient direction in FWI. Depending on the size of wavefield, defined by the model and data, the gradient evaluation, in general, requires large memory space/disk storage in order to store the history of the source wavefield. Storing the entire wavefield is certainly not practical in the case of large 3D models. Boundary saving schemes are alternate viable solutions (Berkhout 1988; Clapp 2008; Rakness and Weibull, 2016; Yang et al., 2016), but at the cost of an additional wavefield extrapolation. Also, techniques based on wavefield compression are promising due to their capability of maintaining a balance between computational time and storage (Unat et al., 2009; Dalmau et al., 2014; Boehm et al., 2016). However, the trade-off between the degree of accuracy and the distortions generated while compressing and decompressing the wavefield in a complex model (Mittal and Vetter, 2016) is complex. Also to mitigate the computational overburden, Sirgue et al. (2008) intermix the time domain formulation of FWI with the frequency domain. They calculate the wavefield in time domain followed by a discrete Fourier transform on the fly followed by gradient direction evaluation in the frequency domain. However, the associated computational leverage and the accuracy of this approach reduce with wider frequency bandwidth used in the inversion process. Alternatively, Kalita and Alkhalifah (2017) reduce the computational overhead by

representing the source wavefield by its peak amplitude and its arrival time. However, this sparse representation of source wavefield, also known as excitation approximation (Chang and McMechan, 1986), doesn't account for multipathing of the source side (Nguyen and McMechan, 2013).

In this study, we extend the concept of the excitation approximation (ExA) to elastic FWI. Thus, it preserves all the benefits mentioned in Kalita and Alkhalifah (2017) in computing the descent direction. Namely, it inherits the mitigation of additional wavefield extrapolation from the boundary. Neither it requires storing the entire source wavefield. Moreover, it reduces the FLOPs, hence, the computational time in evaluating the approximated gradient direction. In addition, ExA removes some undesired long wavelength features from the descent direction that are often generated because of SS correlations, thus, results in a cleaner descent direction compared to its conventional counterpart. The outline of this article is as follows. We start the theory section with a discussion on the mode-separation issues associated with the gradient computation process in regular elastic FWI. After that, we review the features of ExA in acoustic case (Kalita and Alkhalifah, 2016a; Kalita and Alkhalifah, 2017). Next, we introduce ExA in elastic FWI. In the example section, we invert for P and S wave velocities of modified Marmousi II model using ExA. Lastly, we show the possibility of applying elastic FWI using ExA in a real OBC (ocean bottom cable) data set from the North Sea, where subsurface anisotropy is expected in deep layers.

Elastic full waveform inversion

The goal of FWI is to find an optimal solution that minimizes the data mismatch between observed (d_o) and modeled (d_m) data. Among many choices, we choose the zero-lag cross correlation objective function (Routh et al., 2011a; Routh et al., 2011b; Choi and Alkhalifah, 2012), which is defined by:

$$E = -\sum_r \left\{ \hat{d}_m(\mathbf{p}) \cdot \hat{d}_o \right\} \quad (1)$$

where

$$\hat{d}_m(\mathbf{p}) = d_m(\mathbf{p}) / \|d_m(\mathbf{p})\| \quad (2)$$

and

$$\hat{d}_o = d_o / \|d_o\|. \quad (3)$$

The gradient of this objective function with respect to a model parameter $\mathbf{p}$ is given by (Rakness and Weibull, 2016)

$$\frac{\partial E}{\partial \mathbf{p}}(\mathbf{x}) = \int \left[\frac{\partial c_{ijkl}}{\partial \mathbf{p}}(\mathbf{x}) \frac{\partial u_l}{\partial x_k}(\mathbf{x}, t) \frac{\partial u_i^a}{\partial x_j}(\mathbf{x}, t_{\max} - t) \right] dt \quad (4)$$

where c_{ijkl} represents the elastic constants as a function of space coordinates $\mathbf{x}$; The particle displacements, u and u^a , denote the source and adjoint wavefields, respectively. The maximum recording time is denoted by $t_{\max}$.

The source wavefield, u , is a solution of elastic wave equation,

$$\rho(\mathbf{x}) \frac{\partial^2 u_l}{\partial t^2}(\mathbf{x}, t) - \frac{\partial}{\partial x_j} \left[c_{ijkl}(\mathbf{x}) \frac{\partial u_l}{\partial x_k}(\mathbf{x}, t) \right] = f_i(\mathbf{x}_s, t) \quad (5)$$

where ρ and f indicate the density and seismic source at a position, $\mathbf{x}_s$. The adjoint wavefield, u^a , can be computed by backpropagating the following adjoint source,

$$f^a(\mathbf{x}_r, t) = \frac{1}{\|\hat{d}_m(\mathbf{p})\|} \left\{ \hat{d}_m(\mathbf{p}) \left(\hat{d}_m(\mathbf{p}) \cdot \hat{d}_o \right) - \hat{d}_o \right\} \quad (6)$$

Unlike acoustic media, the source wavefield (u) and the adjoint wavefield (u^a) include both P- and S-waves, which means that the gradient direction in eq. (4) is measured by not only PP correlation but also PS, SP and SS correlations. Figure 1 shows the sensitivity kernel (Woodward 1992; Tromp et al., 2005) of P- and S-wave velocities from a pressure source on the water surface (red dot) and vertical displacement on the sea bottom (blue dot) assuming an OBC survey. The sensitivity kernel for the P-wave velocity shows nice banana-shaped long wavelength kernel as many previous works showed for acoustic FWI (Djebbi and Alkhalifah, 2013; Kalita and Alkhalifah, 2017). Compared to the P-wave velocity, the S-wave velocity perturbation shows more complicated features. This is because, as also supported by the radiation patterns in Appendix A, the sensitivity kernel of P-wave velocity includes only PP wave while the sensitivity kernel of S-wave velocity includes all PP, PS, SP and SS waves (Figure 2). Notice that the SS radiation pattern (Figure A1) of the S-wave velocity perturbation includes 180° opening angle, which causes a long wavelength update (Figure 2d; Miller et al., 1987). The PS wave is a main component to recover the S-wave velocity (Hardage et al., 2011) and, in our experience, this long wavelength update from the SS wave is not beneficial. For this reason, the mode-separation technique (Wang and Cheng, 2017) is required to improve the performance of elastic FWI. However, mode-separation in anisotropic media, which requires an additional step of solving the Christoffel equation (Tsvankin and Grechka, 2011), is expensive (Yan and Sava, 2009).

P-wave ExA for elastic FWI

As an alternative way to separate wave mode, we suggest the excitation approximation in elastic FWI. In this study, we focus on ExA for only P-wave in source wavefields so that we can separate PP+PS and SP+SS modes. The fast evaluation of approximated gradient direction with accessing less computational memory is icing on the cake in elastic FWI using ExA.

Review of ExA approach in acoustic FWI

Before introducing ExA in elastic FWI, we briefly review the acoustic ExA that is proposed by Kalita and Alkhalifah (2017). The excitation approximation assumes all the arrivals of the source wavefield other than the maximum are too small to consider (Nguyen and McMechan, 2013; Kalita and Alkhalifah, 2016b). Mathematically, it approximates the source wavefield (u) at a model point ($\mathbf{x}$) generated by a source positioned at $x = x_s$ as,

$$u^{ex}(\mathbf{x}, t; x_s) = u(\mathbf{x}, t; x_s) \delta(t - t_{ex}(\mathbf{x}; x_s)) \quad (7)$$

where t_{ex} is the arrival time for the peak amplitude. The term ex stands for the excitation representation. This strong assumption is valid primarily because of the usual simple nature of the source wavelet. However, it does not take account of the source signature. Kalita and Alkhalifah (2017) redefines ExA under the inversion framework in order to embrace the source signature, $f(t)$, as follows:

$$\begin{aligned} \tilde{u}^{ex}(\mathbf{x}, t; x_s) &= u^{ex}(\mathbf{x}, t; x_s) * f(t) \\ &= u(\mathbf{x}, t; x_s) \delta(t - t_{ex}(\mathbf{x})) * f(t) \end{aligned} \quad (8)$$

where $*$ represents a convolution process in time. Therefore, ExA in the context of FWI replaces the source wavefield by a modified source function where its amplitude is scaled by

the excitation amplitude and its time of origin is shifted by the excitation time. Consequently, the gradient computation process using the definition of eq. (8) does not require storing entire wavefields. Neither it requires the additional wavefield extrapolation, often required to retrieve the source wavefield from the boundary values in the conventional approach. Also, since excitation wavefields contain only one non-zero element, the correlation process involves only one FLOP, rather than the temporal cross-correlation. As a result, ExA approximates the gradient evaluation by accessing a limited memory block and investing shorter time than its conventional counterpart.

P-wave ExA in elastic FWI for OBC data

Unlike acoustic media, particle displacement or velocity fields include both P- and S-waves together in the elastic case. Therefore, it is hard to segregate the excitation time of P-waves in the source wavefields (u) in eq. (4). To solve this issue, as suggested by Nguyen and McMechan (2015) in the context of elastic reverse time migration, we compute the excitation time of the divergence of wavefields (S_v), which includes only P-wave motions. Next, we store the original displacement wavefield at this excitation time. Mathematically,

$$t_{ex} = t_{ex}(\mathbf{x}) = \arg \max_{t \in [1, nt]} \{ |S_v(\mathbf{x}, t)| \} \quad (9)$$

represents the excitation time of P-waves. Now, using the excitation wavefield as mentioned in eq. (8), the approximated gradient computation in eq. (4) is reduced to the following:

$$\frac{\partial E}{\partial \mathbf{p}}(\mathbf{x}) = \frac{\partial c_{ijkl}}{\partial \mathbf{p}}(\mathbf{x}) \frac{\partial u_l}{\partial x_k}(\mathbf{x}, t_{ex}(\mathbf{x})) \frac{\partial \tilde{u}_i^a}{\partial x_j}(\mathbf{x}, t_{\max} - t_{ex}(\mathbf{x})) \quad (10)$$

where $\tilde{u}^a$ is the adjoint wavefields from the modified adjoint source, which is given by the temporal cross-correlation of source-function with the conventional adjoint source in eq. (6).

This modification, according to Kalita and Alkhalifah (2017), arises because the source

wavefields ($\partial u_l / \partial x_k$) at excitation time in eq. (10) needs to be convolved by the source signature as shown in eq. (8). Instead, it is compensated through the adjoint equation in eq. (10) by the temporal cross-correlation process of the adjoint source in eq. (6) with the source signature prior to its reverse propagation in time. As shown above, the first advantage of ExA is the fast calculation of the approximated gradient direction and less memory to store source wavefields. This is because the cross correlation of source and adjoint wavefields is only conducted at the excitation time when the P-wave has its maximum amplitude over the total recording time on each grid point. In elastic FWI, the second advantage of ExA is the automatic mode-separation between P-wave induced (PP and PS) and S-wave induced (SP and SS) correlations. Figure 3 shows the sensitivity kernels of P- and S-wave velocities using P-wave ExA. For the S-wave velocity, the sensitivity kernel looks like a summation of PP and PS sensitivity kernels (Figures 2a and 2b). This is because we choose excitation time for the P-wave in the source wavefields, thus the approximated gradient direction automatically ignores SP and SS correlations.

It is noteworthy that mode separation in anisotropic media for conventional FWI, albeit rare, is expensive. However, we can easily extend our approach to anisotropic FWI for marine environments unless strong anisotropy exists in near surface. Despite the presence of S-waves in the divergence of wavefields due to anisotropy, the direct P-arrival from the source is still the strongest thanks to the source (generally airgun), which generates only the P-wave in the water. Unlike conventional mode-separated anisotropic FWI for offshore datasets, P-wave ExA approach does not require exact mode-separated potential fields because we only use the divergence wavefields to choose the excitation time of P-wave. Then, the approximated gradient direction is calculated using the original displacement wavefields, but only at the excitation time as shown in eq. (10).

Synthetic example: modified Marmousi-II model

To verify the advantages of P-wave ExA on elastic FWI for OBC data, we apply the FWI on the Marmousi II model (Figure 4). The original Marmousi model has a soft sea bottom, which induces slow S-wave velocity. However, to avoid numerical dispersion, S-wave velocities are modified in this example. For the density, we use a homogeneous model (1g/cm^3) with no updating of it during FWI. In the elastic multi-parameter FWI, the structural similarity of P- and S-wave velocities can be an issue because of the trade-offs between P- and S-wave velocities (Köhn et al., 2012; Wang et al., 2016). These trade-offs between P- and S-wave velocities are originated from PP correlation at intermediate opening angle (Figure A1). However, the PP kernel in the S-wave velocity is not enough strong (Figure 1b and Figure 2), which means that the trade-offs can be reduced if we have enough strong S-waves in multi-component data (Oh and Alkhalifah, 2017a; Oh and Alkhalifah, 2017b).

The frequency range is from 3 to 10 Hz with a peak frequency at 5 Hz. Water depth is 200 m. The initial models are obtained by smoothing the true velocities. To scale the gradient direction (descent direction) for each parameter, we first apply the diagonal of pseudo-Hessian matrix (Shin et al., 2001). Then, the vectors for the descent direction of each parameter are normalized by their maximum value so that the update range can be limited from -1 to 1 (Ha et al., 2009). Finally, we apply fixed step-lengths for P- (0.05 km/s) and S-wave velocities (0.03 k/s).

For the P-wave velocity, the P-wave ExA (Figure 5d) produces nearly equivalent ExA descent direction to the conventional method (Figure 5a) because the P-wave velocity generates only PP waves (Appendix A). However, for the S-wave velocity (Figure 6), the ExA descent direction (Figure 6d) shows different features with the conventional descent direction (Figure

6a). The descent direction of S-wave velocity from the conventional method suffers from undesired long wavelength features (yellow arrows), which are induced by S-wave induced correlations (Figure 6c). Particularly, these long wavelength features are the product of SS correlations (Figure 2d), which also have strong diving components at 180° opening angle in their radiation patterns (Figure A1). On the other hand, the descent direction from P-wave ExA (Figure 6d) does not include SP and SS correlations thus the ExA descent direction is nearly equivalent to the mode-separated descent direction (Figure 6b). These long wavelength features from SS correlations impede the overall FWI procedure. Once we generate this long wavelength updates from SS correlation, FWI works to remove these updates in the next iteration. As a result, the convergence rate of the conventional method is slower compared to ExA, which does not contain SS correlations (Figure 7).

Real data: 2C 3D North Sea OBC data

To verify the feasibility of multi-parameter elastic FWI with P-wave ExA to real data, we apply elastic FWI to 2C 3D OBC data set from the North Sea, which includes vertical and inline components. The maximum offsets are about 5 and 1 km along inline and crossline, respectively. For migration purposes, direct waves are muted and each component is separately processed (Szydluk et al., 2007), thus it is hard to trust amplitude information of wavefields. For this reason, the zero-lag cross correlation objective function in eq. (1) is used to perform FWI to this dataset. In addition, we apply a two-stage FWI for each component (Sears et al., 2010) since it is also hard to trust the relative amplitudes of horizontal and vertical components. We first apply acoustic FWI for vertical components that mainly contains P-waves. Then, we apply elastic FWI for the inline component to additionally match PS waves (Figure 8a). The initial P-wave velocity (Figure 8b) is built by smoothing the tomography result (Figure 9a). The FWI is conducted for data with frequencies ranging from 2.75 to 10 Hz. We randomly choose 200 sources out of the total of 3400 at each iteration to avoid artifacts (Díaz and Guitton, 2011). To optimize the descent direction, we also use fixed step-lengths for P- and S-wave velocities with pseudo-Hessian matrix as we did in synthetic example. To stabilize FWI, the updated velocities are constrained from 1 km/s to 5 km/s and from 0.6 km/s to 2.8 km/s for P- and S-wave velocities, respectively.

For acoustic FWI of the vertical component, we apply the multi-stage inversion suggested by Oh and Alkhalifah (2017c). At first, envelope-based inversion is applied to capture long-wavelength structures of the area and then zero-lag cross correlation objective function is applied to obtain the velocity model with higher resolution. For a fair comparison, acoustic FWI is conducted by the conventional boundary saving approach (Rakness and Weibull,

2016). In the 2nd stage, we conduct elastic FWI for the inline component from the P-wave velocity model (Figure 10a) obtained in the 1st stage. With 25m grid spacing, the total number of grid points are 520×304×200 including CPML boundaries (Rodenm and Gedney, 2000). Total recording time is 4 sec with 2001 time samples. This huge 3D FWI is conducted by MPI-based time-domain elastic FWI code using the 4th-order finite difference on a staggered grid (Graves, 1996), in which the modeling process is parallelized over shots and subdomains (Bohlen, 2002). The density is assumed to satisfy Gardner's formula (Gardner et al., 1974) and it is not updated. The initial S-wave velocity model can be estimated by inverting the P-wave velocity and utilizing background v_p/v_s information. In our example, background v_p/v_s information is available from the tomography results (Figure 9). However, the slow S-wave velocities near soft sea bottom (Figure 9b) cause severe numerical dispersion with 25m grid spacing. To avoid these numerical dispersions, we build up an initial S-wave velocity (Figure 10b) based on a fixed Poisson's ratio (0.25) so that shallow area has enough high S-wave velocity. For this reason, P-S waves can be cycle skipped during the FWI. For better fitting of wavefields, we take into account the background anisotropic parameters (Thomsen, 1986), which are provided from the tomography (Figures 10c and 10d), into the modeling procedure without any updates.

Before showing FWI results, we first compare the descent directions from the conventional method, mode-separated FWI and P-wave ExA. Since the separation of wave modes is difficult with an anisotropic background model (Zhang and McMechan, 2010), we consider the isotropic background models for a fair comparison between ExA and conventional methods. Figures 11 and 12 show the descent directions of P- and S-wave velocities from the initial models given in Figures 10a and 10b, respectively. The descent directions for the P-wave velocity using ExA and the conventional approach are almost

identical (Figure 11). However, those for the S-wave velocity are significantly different as shown in Figure 12. The conventional descent direction for the S-wave velocity as shown in Figure 12a includes long-wavelength structures, which are induced because of SS correlations (Figure 12c). Also, these long wavelength updates in vertical slices (Figure 12c) are most likely unreasonable considering the previous study of the area which favors the dominant horizontal layering (Szydluk et al., 2007; Sava and Alkhalifah, 2015; Ravasi et al., 2016; Alkhalifah et al., 2016). In addition, we observe that the minimization process keeps trying to remove these long-wavelength features, once updated during the early iterations of FWI. As a result, the S-wave velocity updates suffer from a slow rate of convergence. On the other hand, P-wave ExA provides relatively sharp descent directions for S-wave velocity with distinct horizontal layering because of its intrinsic nature of automatic selection of PP and PS modes over the rest, if any. For this reason, the ExA descent direction resembles the mode-separated gradient direction as shown in Figure 12b.

Figure 13 shows the inverted models using the conventional method and P-wave ExA. Because the convergence rate of the conventional approach is slow due to the updates from the SS mode, only minor changes are observed in the inverted model. In terms of the computational speed, the conventional method is also slower than P-wave ExA. On the super computer in KAUST (so-called ‘Shaheen II’), which is based on Cray XC40, the conventional boundary saving approach takes 22.4 minutes to complete one iteration in FWI while P-wave ExA takes 17.91 minutes because P-wave ExA does not require additional forward modeling for reconstructing source wavefields

On the other hand, the inverted model using the P-wave ExA offers some updates to the S-wave velocity model (Figure 13b). As additionally expected from the tomography result (Figure 9b), the S-wave velocity decreases after FWI. However, because PP and PS modes of

the S-wave velocity perturbation do not include wide-opening angle components (Figure 2 and Figure A1) that provide long wavelength updates, FWI updates concentrate on the short wavelength structures.

Figure 14 shows the seismogram obtained along the black dashed line when the source is located at the black dot in Figure 8b. After acoustic FWI in 1st stage (Figure 14b), we observe that P-waves in the vertical component are well matched at near offset (red arrows) while, at the far offset, the observed data has faster velocity (blue arrows) that might be caused by subsurface anisotropy. This is the reason why we use background anisotropic parameters in elastic FWI. After the 2nd stage using elastic FWI of the inline component, the PS waves are partially matched compared to the data from the initial model, which includes an initial P-wave velocity (Figure 8b), fixed Poisson's ratio (0.25) and density obtained by Gardner's equation. However, because the background S-wave velocity is not inverted after FWI, the modeled data still looks unsatisfactory. One more issue is the Scholte wave, which propagates on the interface between water and sea bottom. The Scholte wave is not observed in the real data while it is appeared in the synthetic data. This is because of the hard sea bottom in our FWI. However, the influence of Scholte wave might not be strong thanks to zero-lag cross correlation norm (Routh et al., 2011a). As Guitton and Alkhalifah (2016) also showed, the influence of the S-wave velocity is not significant in marine OBC data so that we can still get a good P-wave velocity in acoustic FWI. The angle domain common image gathers (Figure 15; Sava and Fomel, 2003) are also flattened after the second stage FWI particularly at the deeper area around the caprock. Figure 16 shows the velocity comparison over the well path that starts at red dot on the top and ends at the blue dot at the bottom in Figure 8b. The well log velocities are upscaled for visualization. Below 2.3 km in depth, the inverted velocities resemble the well log velocities. However, at the shallower depth where we expect strong

anisotropy as shown in Figure 10, inverted S-wave velocity is overestimated.

We suspect that, because we do not invert for anisotropic parameters, the influence of η might be absorbed by the S-wave velocity due to the trade-off supported by the radiation pattern in Figure A1. For a more successful FWI, we require elastic VTI (vertical transverse isotropic) inversion, which we will investigate in the future.

For Peer Review

Conclusions

To reduce the computational cost of multi-parameter anisotropic elastic FWI for OBC data, we proposed an elastic FWI using the P-wave excitation amplitude of the source wavefields. The excitation approximation assumes all the arrivals of the source wavefields other than the maximum are too small to consider, thus the gradient direction is approximated by being computed at only excitation time. For this reason, ExA approach offers fast FWI in huge 3D elastic media. In addition, because we choose only the maximum energy of P-wave in the source wavefield, the ExA descent direction automatically ignores unwanted SP and SS correlations, which offers separation between PP+PS and SP+SS modes. The numerical example for modified Marmousi II model shows the conventional descent direction for the S-wave velocity suffers from undesired long-wavelength features induced by SS correlation. In the real data example from the North Sea, we also observe that these long-wavelength features decrease the convergence rate of the conventional FWI for the S-wave velocity. Although multipathing is a theoretical limitation of the ExA approach, it does not significantly degrade the quality of the inversion process.

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Appendix A: Radiation patterns of elastic VTI parameters

In Appendix A, we show the reflection patterns of elastic VTI (vertical transverse isotropic) parameters that are helpful to interpret the FWI results for real data. To generate modeled data in the real data example, we use the VTI parameterization, $(v_p, v_s, \varepsilon, \eta)$, suggested by Alkhalifah and Plessix (2014) as parameterized by

$$\begin{pmatrix} C_{11} \\ C_{33} \\ C_{13} \\ C_{55} \end{pmatrix} = \begin{pmatrix} \rho v_p^2 \\ \rho v_p^2 / (1 + 2\varepsilon) \\ \rho \left[\sqrt{\left(\frac{v_p^2}{1 + 2\varepsilon} - v_s^2 \right) \left(\frac{v_p^2}{1 + 2\eta} - v_s^2 \right)} - v_s^2 \right] \\ \rho v_s^2 \end{pmatrix}, \quad (\text{A-1})$$

where v_p and v_s are horizontal P- and vertical S-wave velocities. Because anisotropic parameters are not updated in our example, the choice of parameterization does not affect the overall FWI process. However, the radiation pattern analysis helps us to interpret multi-parameter FWI result (Operto et al., 2013).

The radiation pattern of the partial derivative wavefields in terms of the elastic constants (C_{ijkl}) for P-P, P-SV and SV-SV scatterings can be defined by (Pan et al., 2016; Oh and Alkhaliah, 2016)

$$\mathbf{R}_m^{P-P}(\theta_i, \theta_d) = \mathbf{e}_{P_d}^T \mathbf{M}_m^P \mathbf{e}_{P_d}, \quad (\text{A-2})$$

$$\mathbf{R}_m^{P-SV}(\theta_i, \theta_d) = \mathbf{e}_{SV_d}^T \mathbf{M}_m^P \mathbf{e}_{P_d}, \quad (\text{A-3})$$

and

$$\mathbf{R}_m^{SV-SV}(\theta_i, \theta_d) = \mathbf{e}_{SV_d}^T \mathbf{M}_m^{SV} \mathbf{e}_{SV_d}. \quad (\text{A-4})$$

where

$$\begin{pmatrix} \mathbf{e}_{P_d} & \mathbf{e}_{SV_d} \end{pmatrix} = \begin{pmatrix} \sin \theta_d & \cos \theta_d \\ \cos \theta_d & -\sin \theta_d \end{pmatrix} \quad (\text{A-5})$$

The matrix $\mathbf{M}$ is the 2×2 moment tensor in 2D as expressed by

$$\mathbf{M}_m = \begin{pmatrix} \frac{\partial C_{11}}{\partial m} \varepsilon_{xx}^{k_i} + \frac{\partial C_{13}}{\partial m} \varepsilon_{zz}^{k_i} & 2 \frac{\partial C_{55}}{\partial m} \varepsilon_{xz}^{k_i} \\ 2 \frac{\partial C_{55}}{\partial m} \varepsilon_{xz}^{k_i} & \frac{\partial C_{13}}{\partial m} \varepsilon_{xx}^{k_i} + \frac{\partial C_{33}}{\partial m} \varepsilon_{zz}^{k_i} \end{pmatrix} \quad (\text{A-6})$$

where

$$\begin{pmatrix} \varepsilon_{xx}^{P_i} & \varepsilon_{xx}^{SV_i} \\ \varepsilon_{zz}^{P_i} & \varepsilon_{zz}^{SV_i} \\ \varepsilon_{xz}^{P_i} & \varepsilon_{xz}^{SV_i} \end{pmatrix} = \begin{pmatrix} \sin^2 \theta_i & \sin \theta_i \cos \theta_i \\ \cos^2 \theta_i & -\sin \theta_i \cos \theta_i \\ \sin \theta_i \cos \theta_i & (\cos^2 \theta_i - \sin^2 \theta_i) / 2 \end{pmatrix} \quad (\text{A-7})$$

The two angles θ_i and θ_d denote the incidence and diffraction angles departing from z -axis. To convert the scattering pattern to the reflection pattern (Gholami et al., 2013; Alkhalifah and Plessix 2014), we reformulate the scattering radiation patterns in terms of the opening angle assuming the reflection from the horizontal reflector in the isotropic background media as follows (Oh and Alkhalifah, 2016):

$$\theta_o^{P-P, SV-SV} = \theta_d^{P, SV} - \theta_i^{P, SV} \quad (\text{A-7})$$

where

$$\theta_d^{P, SV} = -\theta_i^{P, SV} \quad (\text{A-8})$$

and

$$\theta_o^{P-SV} = \theta_d^{SV} - \theta_i^P \quad (\text{A-9})$$

where

$$\theta_d^{SV} = \sin^{-1} \left(\frac{v_s}{v_p} \sin(-\theta_i^P) \right) \quad (\text{A-10})$$

Figure A1 shows the reflection radiation pattern in terms of the opening angle. The P-wave velocity perturbation only generates isotropic PP reflections (Tarantola, 1986), while the influence of ε perturbation is dominant at the narrow opening angle for PP reflection. The PP and PS reflection patterns of the S-wave velocity and η resemble each other, which indicates that these two parameters are hard to be detached from the data.

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Figure captions

Figure 1 The sensitivity kernels of (a) P- and (b) S-wave velocity perturbations in elastic FWI for OBC data. The red and blue dots indicate the source (explosive source) location at water surface and the receiver (vertical displacement) location on sea bottom (yellow line), respectively.

Figure 2 The sensitivity kernels of the S-wave velocity perturbation: (a) PP, (b) PS, (c) SP and (d) SS correlations of the source and adjoint wavefields. The noises from the receiver (7 km in distance) in PP and PS modes might be the numerical errors caused by mode separation because they are cancelled out each other in original sensitivity kernel (Figure 1).

Figure 3 The sensitivity kernels of (a) P- and (b) S-wave velocity perturbations using ExA in elastic FWI for OBC data.

Figure 4 The true (and b) and initial (c and d) P- (a and c) and S-wave (b and d) velocities of modified Marmousi-II model. The S-wave velocities are modified to avoid numerical dispersion.

Figure 5 The descent directions for the *P-wave velocity* at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

Figure 6 The descent directions for the *S-wave velocity* at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

Figure 7 The inverted P-wave (a and c) and S-wave (b and d) velocities using the conventional method (a and b) and P-wave ExA (c and d).

Figure 8 (a) The schematic diagram illustrating the FWI strategy for 2C Volve data set and (b) initial P-wave velocity after smoothing the tomography result in Figure 9a.

Figure 9 The tomography results for (a) P-wave and (b) S-wave velocities for comparison.

Figure 10 The initial models for the elastic FWI of inline components. (a) P-wave velocity from the acoustic FWI of vertical component, (b) S-wave velocity using fixed Poisson's ratio (0.25) and smoothed anisotropic parameters from tomography results (c and d).

Figure 11 The descent directions for the *P-wave velocity* from (a) conventional method, (b) mode-separated PP + PS, (c) mode-separated SP + SS and (d) P-wave excitation amplitude.

Figure 12 The descent directions for the *S-wave velocity* from (a) conventional method, (b) mode-separated PP + PS, (c) mode-separated SP + SS waves and (d) P-wave excitation amplitude.

Figure 13 The inverted S-wave velocities from the elastic FWI of the inline component using (a) the conventional method and (b) the P-wave ExA.

Figure 14 Comparisons of vertical (a and b) and inline (c and d) components of observed and modeled data from initial model in Figure 8b (a and c), (b) inverted model after acoustic FWI and (d) inverted model after elastic FWI using P-wave ExA. The source is located on the black dot and receivers are located along black dashed line in Figure 8b. The acoustic modeling is used for (a and b) and elastic modeling is used for (c and d).

Figure 15 Angle domain common image gathers along the black dashed line in Figure 8b from PP (a and b) and PS (c and d) waves for the initial model (a and c) and inverted model (b and d).

Figure 16 Vertical profiles extracted from the well, which starts from the red dot on the top and ends at the blue dot at the bottom in Figure 8b: (a) P- and S-wave velocities and (b) V_p/V_s ratio. S-wave velocities for shallow depth are unavailable.

Figure A1 The reflection patterns from elastic VTI parameter perturbations. The angle indicates opening angle between a source and a receiver via subsurface horizontal reflector. The critical angle is extracted from the 0.25 Poisson's ratio based on Snell's law for PS reflection.

Figure 1a The sensitivity kernels of (a) P- and (b) S-wave velocity perturbations in elastic FWI for OBC data. The red and blue dots indicate the source (explosive source) location at water surface and the receiver (vertical displacement) location on sea bottom (yellow line), respectively.

82x29mm (300 x 300 DPI)

Figure 1b The sensitivity kernels of (a) P- and (b) S-wave velocity perturbations in elastic FWI for OBC data. The red and blue dots indicate the source (explosive source) location at water surface and the receiver (vertical displacement) location on sea bottom (yellow line), respectively.

82x29mm (300 x 300 DPI)

Figure 2a The sensitivity kernels of the S-wave velocity perturbation: (a) PP, (b) PS, (c) SP and (d) SS correlations of the source and adjoint wavefields. The noises from the receiver (7 km in distance) in PP and PS modes might be the numerical errors caused by mode separation because they are cancelled out each other in original sensitivity kernel (Figure 1).

82x29mm (300 x 300 DPI)

Figure 2b The sensitivity kernels of the S-wave velocity perturbation: (a) PP, (b) PS, (c) SP and (d) SS correlations of the source and adjoint wavefields. The noises from the receiver (7 km in distance) in PP and PS modes might be the numerical errors caused by mode separation because they are cancelled out each other in original sensitivity kernel (Figure 1).

82x29mm (300 x 300 DPI)

Figure 2c The sensitivity kernels of the S-wave velocity perturbation: (a) PP, (b) PS, (c) SP and (d) SS correlations of the source and adjoint wavefields. The noises from the receiver (7 km in distance) in PP and PS modes might be the numerical errors caused by mode separation because they are cancelled out each other in original sensitivity kernel (Figure 1).

82x29mm (300 x 300 DPI)

Figure 2d The sensitivity kernels of the S-wave velocity perturbation: (a) PP, (b) PS, (c) SP and (d) SS correlations of the source and adjoint wavefields. The noises from the receiver (7 km in distance) in PP and PS modes might be the numerical errors caused by mode separation because they are cancelled out each other in original sensitivity kernel (Figure 1).

82x29mm (300 x 300 DPI)

Figure 3a The sensitivity kernels of (a) P- and (b) S-wave velocity perturbations using ExA in elastic FWI for OBC data.

82x29mm (300 x 300 DPI)

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Figure 3b The sensitivity kernels of (a) P- and (b) S-wave velocity perturbations using ExA in elastic FWI for OBC data.

82x29mm (300 x 300 DPI)

Figure 4a The true (and b) and initial (c and d) P- (a and c) and S-wave (b and d) velocities of modified Marmousi-II model. The S-wave velocities are modified to avoid numerical dispersion.

79x28mm (300 x 300 DPI)

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Figure 4b The true (and b) and initial (c and d) P- (a and c) and S-wave (b and d) velocities of modified Marmousi-II model. The S-wave velocities are modified to avoid numerical dispersion.

79x28mm (300 x 300 DPI)

Figure 4c The true (and b) and initial (c and d) P- (a and c) and S-wave (b and d) velocities of modified Marmousi-II model. The S-wave velocities are modified to avoid numerical dispersion.

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Figure 4d The true (and b) and initial (c and d) P- (a and c) and S-wave (b and d) velocities of modified Marmousi-II model. The S-wave velocities are modified to avoid numerical dispersion.

79x28mm (300 x 300 DPI)

Figure 5a The descent directions for the P-wave velocity at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

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Figure 5b The descent directions for the P-wave velocity at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

79x28mm (300 x 300 DPI)

Figure 5c The descent directions for the P-wave velocity at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

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Figure 5d The descent directions for the P-wave velocity at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

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Figure 6a The descent directions for the S-wave velocity at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

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Figure 6b The descent directions for the S-wave velocity at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

79x28mm (300 x 300 DPI)

Figure 6c The descent directions for the S-wave velocity at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

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Figure 6d The descent directions for the S-wave velocity at 1st iteration from (a) conventional method, (b) mode-separated PP + PS waves, (c) mode-separated SP + SS waves and (d) P-wave ExA.

79x28mm (300 x 300 DPI)

Figure 7a The inverted P-wave (a and c) and S-wave (b and d) velocities using the conventional method (a and b) and P-wave ExA (c and d).

79x28mm (300 x 300 DPI)

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Figure 7b The inverted P-wave (a and c) and S-wave (b and d) velocities using the conventional method (a and b) and P-wave ExA (c and d).

79x28mm (300 x 300 DPI)

Figure 7c The inverted P-wave (a and c) and S-wave (b and d) velocities using the conventional method (a and b) and P-wave ExA (c and d).

79x28mm (300 x 300 DPI)

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Figure 7d The inverted P-wave (a and c) and S-wave (b and d) velocities using the conventional method (a and b) and P-wave ExA (c and d).

79x28mm (300 x 300 DPI)

Figure 8 (a) The schematic diagram illustrating the FWI strategy for 2C Volve data set and (b) initial P-wave velocity after smoothing the tomography result in Figure 9a.

112x66mm (300 x 300 DPI)

Figure 8b (a) The schematic diagram illustrating the FWI strategy for 2C Volve data set and (b) initial P-wave velocity after smoothing the tomography result in Figure 9a.

113x58mm (300 x 300 DPI)

Figure 9a The tomography results for (a) P-wave and (b) S-wave velocities for comparison.

113x58mm (300 x 300 DPI)

Figure 9b The tomography results for (a) P-wave and (b) S-wave velocities for comparison.

112x56mm (300 x 300 DPI)

Figure 10a The initial models for the elastic FWI of inline components. (a) P-wave velocity from the acoustic FWI of vertical component, (b) S-wave velocity using fixed Poisson's ratio (0.25) and smoothed anisotropic parameters from tomography results (c and d).

113x58mm (300 x 300 DPI)

Figure 10b The initial models for the elastic FWI of inline components. (a) P-wave velocity from the acoustic FWI of vertical component, (b) S-wave velocity using fixed Poisson's ratio (0.25) and smoothed anisotropic parameters from tomography results (c and d).

112x56mm (300 x 300 DPI)

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111x56mm (300 x 300 DPI)

Figure 10d The initial models for the elastic FWI of inline components. (a) P-wave velocity from the acoustic FWI of vertical component, (b) S-wave velocity using fixed Poisson’s ratio (0.25) and smoothed anisotropic parameters from tomography results (c and d).

111x56mm (300 x 300 DPI)

Figure 11a The descent directions for the P-wave velocity from (a) conventional method, (b) mode-separated PP + PS, (c) mode-separated SP + SS and (d) P-wave excitation amplitude.

111x56mm (300 x 300 DPI)

Figure 11b The descent directions for the P-wave velocity from (a) conventional method, (b) mode-separated PP + PS, (c) mode-separated SP + SS and (d) P-wave excitation amplitude.

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111x56mm (300 x 300 DPI)

Figure 12b The descent directions for the S-wave velocity from (a) conventional method, (b) mode-separated PP + PS, (c) mode-separated SP + SS waves and (d) P-wave excitation amplitude.

111x56mm (300 x 300 DPI)

Figure 12c The descent directions for the S-wave velocity from (a) conventional method, (b) mode-separated PP + PS, (c) mode-separated SP + SS waves and (d) P-wave excitation amplitude.

111x56mm (300 x 300 DPI)

Figure 12d The descent directions for the S-wave velocity from (a) conventional method, (b) mode-separated PP + PS, (c) mode-separated SP + SS waves and (d) P-wave excitation amplitude.

111x56mm (300 x 300 DPI)

Figure 13a The inverted S-wave velocities from the elastic FWI of the inline component using (a) the conventional method and (b) the P-wave ExA.

112x56mm (300 x 300 DPI)

Figure 13b The inverted S-wave velocities from the elastic FWI of the inline component using (a) the conventional method and (b) the P-wave ExA.

112x56mm (300 x 300 DPI)

Figure 14a Comparisons of vertical (a and b) and inline (c and d) components of observed and modeled data from initial model in Figure 8b (a and c), (b) inverted model after acoustic FWI and (d) inverted model after elastic FWI using P-wave ExA. The source is located on the black dot and receivers are located along black dashed line in Figure 8b. The acoustic modeling is used for (a and b) and elastic modeling is used for (c and d).

104x46mm (300 x 300 DPI)

Figure 14b Comparisons of vertical (a and b) and inline (c and d) components of observed and modeled data from initial model in Figure 8b (a and c), (b) inverted model after acoustic FWI and (d) inverted model after elastic FWI using P-wave ExA. The source is located on the black dot and receivers are located along black dashed line in Figure 8b. The acoustic modeling is used for (a and b) and elastic modeling is used for (c and d).

104x46mm (300 x 300 DPI)

Figure 14c Comparisons of vertical (a and b) and inline (c and d) components of observed and modeled data from initial model in Figure 8b (a and c), (b) inverted model after acoustic FWI and (d) inverted model after elastic FWI using P-wave ExA. The source is located on the black dot and receivers are located along black dashed line in Figure 8b. The acoustic modeling is used for (a and b) and elastic modeling is used for (c and d).

104x46mm (300 x 300 DPI)

Figure 14d Comparisons of vertical (a and b) and inline (c and d) components of observed and modeled data from initial model in Figure 8b (a and c), (b) inverted model after acoustic FWI and (d) inverted model after elastic FWI using P-wave ExA. The source is located on the black dot and receivers are located along black dashed line in Figure 8b. The acoustic modeling is used for (a and b) and elastic modeling is used for (c and d).

104x46mm (300 x 300 DPI)

Figure 15a Angle domain common image gathers along the black dashed line in Figure 8b from PP (a and b) and PS (c and d) waves for the initial model (a and c) and inverted model (b and d).

146x109mm (300 x 300 DPI)

Figure 15b Angle domain common image gathers along the black dashed line in Figure 8b from PP (a and b) and PS (c and d) waves for the initial model (a and c) and inverted model (b and d).

146x109mm (300 x 300 DPI)

Figure 15c Angle domain common image gathers along the black dashed line in Figure 8b from PP (a and b) and PS (c and d) waves for the initial model (a and c) and inverted model (b and d).

101x52mm (300 x 300 DPI)

Figure 15d Angle domain common image gathers along the black dashed line in Figure 8b from PP (a and b) and PS (c and d) waves for the initial model (a and c) and inverted model (b and d).

101x52mm (300 x 300 DPI)

Figure 16a Vertical profiles extracted from the well, which starts from the red dot on the top and ends at the blue dot at the bottom in Figure 8b: (a) P- and S-wave velocities and (b) V_p/V_s ratio. S-wave velocities for shallow depth are unavailable.

112x58mm (300 x 300 DPI)

Figure 16b Vertical profiles extracted from the well, which starts from the red dot on the top and ends at the blue dot at the bottom in Figure 8b: (a) P- and S-wave velocities and (b) Vp/Vs ratio. S-wave velocities for shallow depth are unavailable.

112x97mm (300 x 300 DPI)

Figure A1 The reflection patterns from elastic VTI parameter perturbations. The angle indicates opening angle between a source and a receiver via subsurface horizontal reflector. The critical angle is extracted from the 0.25 Poisson's ratio based on Snell's law for PS reflection.

80x35mm (300 x 300 DPI)