Developing Initial Model for Seismic Full Waveform Inversion Using Conventional Data Processing Tools

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We believe Full waveform inversion (FWI) is capable to be used as a part of seismic data processing routines. In order to check the possibility of using FWI in conventional data processing sequences, we evaluated the effect of different initial models on inversion results. We developed new initial models for full waveform inversion using horizon-guided well interpolation and compared it against initial velocities converted from stacking velocities, with and without dip move-out (DMO) correction. Acoustic full waveform inversion results from Marmousi2 model showed that when the subsurface structure has strong dips, interval velocities which are converted from stacking velocity without dip corrections fail to initialize FWI properly. However, applying dip move-out correction on the seismic data will relax the dip complexities in the velocity analysis stage and a good initial model for FWI could be developed. Alternatively, horizon-guided well interpolation uses velocities derived from well logs and makes an interpolated velocity model along the picked horizon by a constrained post-stack inversion. This makes an initial velocity model for full waveform inversion which ensures the convergence to the correct solution.

1. INTRODUCTION

Full waveform inversion is essentially a data fitting problem with a large number of local minima in the misfit function. Global optimization algorithms are impractical to solve the FWI problem, due to a huge number of model parameters and excessive computational demands. Inevitably, local optimization methods are used to iteratively update an initial guess of the model. The drawback is that these methods are very likely to get trapped in a local minimum of the misfit function. This could happen when samples from simulated data are fitted with inappropriate samples of the observed data. **Figure 1** illustrates two examples of data fitting in FWI. The left panel shows a wrong fitting which tries to match two different samples in observed and calculated data. This problem, which is called cycle skipping, leads the local optimization algorithm to reach a local, rather than global, minimum of the misfit function. The right panel shows correct fitting between observed and calculated data, in which FWI is successfully approaching the global solution. Starting full waveform inversion from high frequencies, i.e. the left panel, is very likely to result in cycle skipping problem. But starting FWI from low enough frequencies, i.e. the right panel, prevents cycle skipping. One of the problems in real applications of FWI is that the lower extents of the recorded frequencies are limited by data acquisition

technologies. Generally, frequencies below a certain value (≈ 5 Hz) are not practically observed. In this paper, we propose an integrated workflow of seismic data analysis to provide the low wavenumber component of the model for FWI. First we use a pre-stack time migrated (PSTM) section which has been produced by conventional data processing flows. A sparse spike reflectivity inversion estimates the reflectivity section of the migrated data, to be used for a horizon-guided well interpolation and acoustic impedance inversion to build the initial model for FWI. Second, in a more realistic situation, we consider a case that no well data is provided. We could build a reliable initial model for FWI by properly picking stacking velocities after dip move-out (DMO) correction. By applying DMO correction, the apparent velocity which is picked through velocity analysis is very close to the true velocity with which seismic waves have traveled. An initial model could be built by converting RMS velocities to interval velocities.

Figure 1 Starting FWI from high frequencies leads to cycle skipping (left), the issue is solved by low frequencies (right).

2. FULL WAVEFORM INVERSION

Full waveform inversion is a local optimization problem which iteratively updates an initial model by minimizing the misfit function, usually defined as the least squares norm of the difference between recorded and calculated data as¹⁾

$$E(p) = \frac{1}{2} \sum_{j=1}^{N_s} \Delta \mathbf{d}_j^t \Delta \mathbf{d}_j^* \quad (1)$$

where, $\Delta \mathbf{d}$ is the residual waveform and superscripts t and $*$ denote transpose and complex conjugate, respectively. Summation is over all sources and p is the model parameter. The gradient of the misfit function at k^{th} iteration for a single frequency is calculated by using adjoint state method as

$$\mathbf{g}_{k,p} = \sum_{j=1}^{N_s} \mathbf{u}_j^t \frac{\partial \mathbf{A}^t}{\partial p} \mathbf{A}^{-1} \Delta \mathbf{d}_j^* \quad (2)$$

where $\mathbf{u}$ is the modeled waveform and $\mathbf{A}$ is the impedance matrix, i.e. the forward modeling operator. The gradient is scaled with pseudo Hessian matrix and the model parameter is updated as

$$p_{k+1} = p_k - \alpha \mathbf{H}^{-1} \mathbf{g}_k \quad (3)$$

Step length α is calculated by a line search along the gradient direction using a parabola fitting method to update the model parameter.

3. FWI INITIAL MODEL BUILDING

In order to build an initial model for full waveform inversion, we used two different strategies. First, we considered a situation where well log data are provided at some locations in the survey area. A horizon-guided interpolation of well data helps to build the low wavenumber component of the background model by constrained post-stack inversion. Second, in a more realistic situation, we considered the case that no well data is available. The idea is that a proper stacking velocity analysis should be capable of estimating low wavenumber velocity model, if the dip complexities are handled properly. We show that dip move-out (DMO) correction can relax the dip effects in the seismic data and move the apparent velocity functions to the vicinity of the true velocity. It means, a conventional velocity analysis after a DMO correction can provide the low wavenumber

component of the background velocity model for initializing FWI.

(1) FWI Initial Model from Well Interpolation

A pre-stack time migrated (PSTM) section is used to develop a reflectivity section through sparse spike inversion²⁾. In a trace by trace process, the best set of spikes which their convolution with known seismic wavelet reproduces the input trace with minimum error are extracted. A global optimization approach is used to detect spikes time lags in the reflectivity series by means of adaptive simulated annealing (ASA) and the amplitudes of the spikes are calculated using a linear least squares method. Since the process is applied on the stacked section, the computational work is negligible and a high resolution section with accurate arrival times is achieved. This reflectivity section is then used at two stages. First, it provides an accurate reference for picking the horizons, either on PSTM or reflectivity section. When the horizons are picked, the available well log data is interpolated along the horizons to expand the well information over all section. The reflectivity section is again used for constrained acoustic impedance inversion using the interpolated well logs³⁾. Considering a known density model, or incorporating empirical equations⁴⁾ the resulting acoustic impedance could be converted to velocity section. Finally, a depth conversion provides an initial model for FWI.

(2) FWI Initial Model from Velocity Analysis

We believe seismic reflection data itself is capable of providing a reliable velocity model, if the dip complexities are handled properly. When seismic reflector is a dipping plane, the stacking velocity which is needed to flatten time CDP gathers is higher than the true velocity with which the energy traveled through the subsurface⁵⁾. We use dip move-out (DMO) correction to remove the dip effects before RMS velocity analysis, and then pick the velocities. DMO correction is a pre-stack partial migration process which can handle even steeply dipped reflectors within a much shorter time compared to pre-stack depth migration. It is usually desirable to apply DMO correction and velocity analysis in a loop for a few times until the best velocity picks are achieved. Here we apply a DMO correction operator on common offset gathers in frequency-wavenumber domain⁶⁾.

4. MARMOUSI2 SYNTHETIC EXAMPLE

Marmousi2 model has been used to evaluate our conventional seismic data processing flow together with FWI. A number of 450 shot gathers, recorded by 900 receivers, on a finite difference grid with intervals of 7.5m have been generated by frequency domain finite difference modeling. Time domain traces are produced by an inverse Fourier transform. A Ricker wavelet with dominant frequency of 15Hz is used as seismic source. All the traces in the generated synthetic data are used in a conventional processing flow to develop the PSTM section shown in **Figure 2**.

(1) FWI Using Well Interpolation Results

The PSTM section is used for the sparse spike reflectivity inversion. After picking the horizons detected in the reflectivity section, the log data from three wells, indicated in **Figure 2** by vertical dashed lines, are interpolated along the horizons. Then, an acoustic impedance inversion using reflectivity section and interpolated well logs is applied to incorporate low frequency information from well logs. Since we used a constant density for this example, the velocity model is directly converted from acoustic impedance section. **Figure 2** shows the PSTM section, reflectivity section and estimated velocity model in time domain. A depth conversion of this model gives a starting model for FWI.

In order to check FWI results using the new initial models we design two frequency sets according to **Table 1**. The first set which we call it *wide band* starts from 2Hz and the second set which we call it *narrow band* starts from 5.33Hz missing the first 5 frequencies. **Figure 3** shows FWI results

Figure 2. PSTM section (top), reflectivity section (middle), and velocity model resulting from well interpolation and acoustic impedance inversion (bottom).

using an initial model which is a smooth version of true model. Although the *wide band* frequency set can obtain a good result, FWI using the *narrow band* frequency set is not converging to the correct solution and obviously the smooth initial model fails to solve the cycle skipping issue. **Figure 4** shows the FWI results using new initial model which is improved by the low wavenumber components from well log interpolation. Now, not only the *wide band*, but also the *narrow band* frequencies could obtain a result which matches the true model.

Table 1. Two sets for FWI with and without low frequencies.

	group 1	group 2	group 3	group 4	group 5	group 6
<i>wide band</i>	2.0, 2.5, 3.0	3.0, 3.5, 4.33	4.33, 5.33, 6.5	6.5, 7.83, 9.5	9.5, 11.5, 14.0	14.0, 17.16, 20.66
<i>narrow band</i>	5.33, 6.5	6.5, 7.83	7.83, 9.5	9.5, 11.5	11.5, 14.0	14.0, 17.16

Figure 3. Top to bottom: smooth initial model, *wide band* FWI, failed *narrow band* FWI, and true model.

Figure 4. Initial model from horizon-guided well interpolation and acoustic impedance inversion (top), *wide band* FWI (middle), and *narrow band* FWI (bottom).

(2) FWI Using DMO Correction and Velocity Analysis Results

A semblance panel for velocity analysis on Marmousi2 dataset before (left) and after (right) DMO correction is shown in **Figure 5**. This panel is formed using the data in the vicinity of horizontal location equal to 6700m. Since the subsurface geology in this area shows steeply dipping layers, the apparent velocity which semblance spectra illustrate is quite larger than the true RMS velocity, shown by black line in **Figure 5**. After applying DMO correction, the new semblance spectra matches well with the true RMS velocity. Picking this accurate velocity trend builds an RMS velocity profile, and interval velocity model in depth could be converted from picked RMS velocities.

Figure 5. Semblance velocity analysis panel without (left) and with (right) DMO correction. Black line shows true velocity.

Figure 6. Initial model converted from picked RMS velocities without DMO correction (top), *narrow band* FWI (bottom).

Figure 7. Initial model converted from picked RMS velocities after DMO correction (top), *narrow band* FWI (bottom).

Interval velocities converted from picked RMS velocities (with and without using DMO correction), and FWI results using these initial models are shown in **Figure 6** and **Figure 7**. The velocity model build without applying DMO correction fails for *narrow band* FWI, due to inaccurate initial model. It is obvious that in the central part of the model, where complex structures appear, the initial model could not handle the dips. **Figure 7** shows the initial model converted from picked velocities after DMO correction and the *narrow band* FWI result using this initial model. Since the dip effect has been relaxed by DMO, the velocity model is good enough to guide FWI to the correct solution

CONCLUSIONS

We examined the possibility of embedding full waveform inversion in the conventional seismic data processing sequence. Two different techniques for building initial velocity models using well log interpolation and velocity analysis have been presented. When well data is available, a reliable low wavenumber model could be built by horizon-guided interpolation and post-stack constrained inversion. In the case that no well data is provided, DMO correction and velocity analysis can estimate a good background velocity model for FWI.

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