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Multiparameter Full-Waveform Inversion for Velocity and Attenuation – Refining the Imaging of a Sedimentary Basin

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SUMMARY

This study deals with the extension of the frequency-domain full-waveform inversion/modelling (FWI) from the acoustic to the viscoacoustic case in application to the wide-aperture seismic data recorded in the Polish Basin. Attenuation was accounted for by introduction of complex velocities. Multiparameter inversion involving P-wave velocity and Q factor produces more focused and clearer images than obtained by the acoustic FWI, however only the absorption effects were analysed. Results strongly depend on the starting Q model used. We tested several starting Q models and conclude that the Q derived from P-wave velocity produces geologically justified results.
Introduction

Recent applications of the frequency domain full-waveform inversion (FWI) provide detailed P-wave velocity models for various geological settings, ranging from overthrust (Ravaut et al., 2004), through sedimentary basin (Malinowski and Operto, 2006) to subduction zone (Operto et al., 2006). In those studies the acoustic approximation for the wave propagation was used, however the waveforms obviously contain much more information, that might be used for a multiparameter inversion, e.g. for the density and attenuation. The most straightforward approach seems to be the viscoacoustic approximation, under which joint inversion for velocity and attenuation might be performed.

Modelling/inversion method

We extended the FWI method presented by Operto et al. (2006) to viscoacoustic media following the work of Song et al. (1995), Hicks et al. (2001) and Pratt et al. (2005). Since we are inverting discrete frequency components, we consider only absorption effects. The attenuation is easily introduced both in forward modelling and inversion by the use of complex velocities (Song et al., 1995):

\[ \tau = \left( \frac{1}{1 + isign \sigma / 2Q} \right) \]  

(1)

where \( c \) is the P wave velocity and \( Q \) is the quality factor of the rock; the attenuation is proportional to the inverse of the quality factor, \( Q^{-1} \). The real velocity \( c \) and the \( Q \) factor are extracted from the complex velocity values. In this work we focus on the application of this software to the real wide-aperture seismic data acquired in the Polish Basin.

Application to GRUNDY 2003 data

The GRUNDY 2003 experiment was carried out in the western part of the Polish Basin (Malinowski et al., 2006). Eight hundred RefTek 125 “Texan” stations with 4.5 Hz geophones were deployed in a 50 by 10 km rectangular area, forming a high-density central line (receiver spacing 100 m, length 50 km, referred as G01 line) and additional 4 parallel profiles with mean receiver spacing of 600 m. Thirty 40-50 kg shots were fired along the G01 profile and 7 shots were put in the side-profiles. Those wide-aperture data were successfully modelled by the FWI method (Malinowski and Operto, 2006), but since we observe in the shot gathers a high decay of the amplitudes, it would be desirable to introduce also the attenuation in the course of modelling. However, the key issue is to provide a good starting model for the \( Q \). By matching the amplitudes of the synthetic data calculated for different values of \( Q \), we estimate the quality factor to be ca. 50. This is rather low value, typical for the shallow sedimentary layers. Thus we test also another constant attenuation model using \( Q = 100 \). To some extent the \( Q \) and \( V_p \) are correlated, hence we have tried to derive the starting \( Q \) model using starting velocity model. As the first attempt, we simply divided \( V_p \) by 100 (Fig. 1c). In the next trial we used the relation proposed by Waters (1978) for VSP data:

\[ \frac{1}{Q_p} = \left( \frac{1000}{V_p} \right)^2 \]  

(2)

where the \( V_p \) is expressed in feet/s. All other parameters of the inversions remains same as in Malinowski and Operto (2006).

Joint inversion for velocity and attenuation generally resulted in the improved velocity models (Fig. 2b-f) with sharper velocity contrasts as compared to the acoustic inversion (Fig. 2a). The clearest images were obtained for the constant starting \( Q = 50 \) (Fig. 2b) and the \( Q = V_p/100 \) (Fig. 2d). However, if we look at the respective inverted \( Q \) models (Fig. 1a, d), it seems that they contain too low \( Q \) values in the deeper part. In turn, although the inverted perturbational model when using constant \( Q = 100 \) and \( Q \) from relation (2) are not so sharp, the recovered \( Q \)
models, shown in Fig. 1b, f, are most plausible from the geological and petrophysical point of view (e.g. $Q=100-200$ for the Zechstein strata). In all cases, the introduction of the attenuation improves the data fit in the frequency domain, especially for the lower starting $Q$, as compared to the acoustic modelling (Fig. 3). Accordingly, the cost function reduction becomes more significant: from maximum of 10% for acoustic inversion to 30-40% in viscoacoustic modelling.

**Conclusions**

In case of the GRUNDY 2003 data, the introduction of the attenuation in the FWI produces clearer velocity models, which are however dependent on the starting $Q$ model used. This dependence is much stronger for the recovered $Q$ models. The use of the empirical relation between $V_p$ and the $Q$ allowed us to obtain geologically consistent $Q$ model. We stress however, that only the absorption effects have been analysed yet. In order to introduce the dispersion, we have to re-organize the whole modelling flow and invert all frequency component simultaneously. The work on multiparameter inversion including also the density is in progress now.

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**References**


Figure 1. Starting and inverted Q models: a) inverted model for constant starting $Q=50$; b) inverted model for constant starting $Q=100$; c) starting model, $Q=V_p/100$; d) inverted model; e) starting Q model from relation (2); e) inverted model. Note the different colour scales.
Figure 2. Perturbational models obtained by the FWI at 13 Hz; a) acoustic inversion; b) viscoacoustic inversion, starting constant $Q=50$; c) viscoacoustic inversion, constant $Q=100$; d) viscoacoustic inversion, $Q=Vp/100$; e) viscoacoustic inversion, $Q$ from relation (2).

Figure 3. Plot of the datafit in the frequency domain (real part vs offset) at 5 Hz component for selected shot gather. Red curve are the observed data, green and blue – calculated data at 1st and 10th iterations. a) acoustic inversion; b) viscoacoustic inversion