Introduction

In seismic exploration, internal multiple removal is one of the most challenging problems. Various methods have been developed to attenuate internal multiples and no companies claimed that they have solved this problem completely. Among these methods, Delft’s feedback method (Berkhout and Verschuur, 1997) and Jackubowicz’s convolution-correlation method (Jakubowicz, 1998) require a priori subsurface information about the multiple generators, while the inverse scattering series (ISS) internal multiple attenuation (IMA) method (Araújo, 1994; Weglein et al., 1997) can predict all internal multiples without requiring any subsurface information and identifying any multiple generators. It is fully data-driven and can predict correct time and approximate and well-understood amplitude of the internal multiples.

Internal multiples are generated by a series of strong subsurface reflectors. For example, internal multiples can be generated between the sea-floor and the salt structures and they have similar travel-time with primaries from the pre-salt reservoir (Li et al., 2016). Without removing these multiples will affect the reservoir identification and characterization. Therefore, removing certain target internal multiples that are interfered with the primaries is our priority in seismic processing. By identifying certain multiple generators, the IMA method can reduce computational cost and improve efficiency to predict and remove the target internal multiples under strong reflectors in the reservoir. In this abstract, the IMA method is modified and improved first and then tested on synthetic and field data to show its availability and reliability for target internal multiple removal.

Theory

The internal multiple attenuation algorithm is derived from the inverse scattering series (Araújo, 1994; Weglein et al., 1997). For a normal incidence wave with an 1D earth, 

\[
b_3(k) = \int_{-\infty}^{\infty} dz_1 b_1(z_1) e^{ikz_1} \int_{z_1}^{z_1-\varepsilon} dz_2 b_1(z_2) e^{-ikz_2} \int_{z_2+\varepsilon}^{\infty} dz_3 b_1(z_3) e^{ikz_3},
\]

where \( b_1(z) = \int_{-\infty}^{\infty} b_1(k) e^{-ikz} dk, \) \( k = 2\omega/c_0 \) is vertical wavenumber and \( c_0 \) is reference velocity. \( b_3 \) is the predicted first-order internal multiple. For a spike wave, \( b_1(k) = D(\omega) \), which is input data. \( b_1(z) \) corresponds to the reference velocity FK migration of the normal incidence wave. \( z_i (i = 1, 2, 3) \) represents pseudo-depth in the FK migration. The parameter \( \varepsilon \) is introduced to insure that the relations \( z_1 > z_2 \) and \( z_3 > z_2 \) are strictly satisfied. Providing the input data, this algorithm can predict all first-order internal multiples for all horizons at once, hence, it’s fully data-driven and does not require any subsurface information.

Since internal multiples exist widely in the whole data, they are difficult to remove all at once. Furthermore, internal multiples are usually interfering with or proximal to primaries, especially in the pre-salt reservoir, this will make multiples further difficult to remove. Therefore, removing certain target internal multiples in the reservoir is a better choice. It can reduce computational cost and improve efficiency for predicting and removing the target internal multiples that are interested in. The IMA method is modified and improved by identifying certain multiple generators,

\[
b_3(k) = \int_{z-d_1}^{z+d_1} dz_1 b_1(z_1) e^{-ikz_1} \left[ \int_{z_1-\varepsilon}^{\infty} dz_2 b_1(z_2) e^{ikz_2} \right]^2 .
\]

First of all, this algorithm is reduced from three integrals to two integrals, it reduces the computational cost and enhances the efficiency of multiple prediction. Secondly, by identifying certain internal multiple generators at \( z \) and its width \([−d_1, d_1]\), the modified and improved IMA method can predict only the target internal multiples that are interested in and it will further reduce the computational cost by shrinking the integral range. To impose the strict lower-higher-lower relationship, a parameter \( \varepsilon \) is introduced to insure that the relations \( z_2 > z_1 \) is satisfied. Finally, the modified IMA method contains the merit of the previous IMA method (Araújo, 1994). It is still fully data-driven and does not require any subsurface information. Moreover, it will attenuate effectively the target internal multiples and help interpreters to identify reservoirs. Even the above idea is in 1D case, it can also be extended to 2D and 3D.
Numerical examples

The modified IMA method is tested on synthetic and field data. Figure 1(a) represents the synthetic data that is generated by an acoustic model. It contains three primaries and corresponding internal multiples that generated by generator 1 (first primary) and generator 2 (second primary). Figures in right column are their corresponding trace plots. The internal multiples for generator 1 and generator 2 are predicted separately by the modified IMA method. The predicted internal multiples due to generator 1 are shown in Figure 1(b) and they have correct travel-time and approximate amplitude. Figure 1(c) shows the multiple removal after adaptive subtraction, it can be seen that only internal multiples that due to generator 1 are removed. Then, the internal multiples due to generator 2 are predicted as shown in Figure 1(d). After adaptive subtraction, Figure 1(e) represents the internal multiples due to generator 2 are removed. From this example, we can conclude that the internal multiples can be removed step by step for each multiple generator separately, and this can help data processor remove target internal multiples for certain generators in the reservoir. Figure 2 shows a noised synthetic data example, which S/N is 10. Similar conclusion is obtained that the target internal multiples can be predicted and removed separately.

Figure 3 demonstrates the first field data before and after internal multiple removal. The target internal multiples due to the generator (the blue arrow in Figure 3) are predicted and removed in the target reservoir between 3.5s and 5.0s by using other method and the modified IMA method as shown in Figures 3(b) and 3(c). At about 4.2s, there are several strong reflectors which are the generators of the target internal multiples. The corresponding internal multiples can be interpreted as primaries mistakenly. After multiple removal, Figure 3(b) shows that the internal multiples are not removed completely by using other method, while after multiple removal by using the modified IMA algorithm, they are effectively and successfully attenuated at the red arrow area as shown in Figure 3(c). Figure 4 shows the second field data. It can be seen that the target internal multiples are mainly generated by the strong reflectors – coal seams at 0.9s 1.0s (in green bracket area). They are interfering with and damaged the target primaries (blue arrow) at around 1.1s. After multiple removal, there are a lot of multiple residues by using other method as shown in Figure 4(b), while Figure 4(c) presents the target internal multiples are removed effectively by using the modified IMA method and the damaged primaries are also recovered almost completely. These two field data examples show that the modified IMA method can remove the target internal multiple effectively for certain strong multiple generators in the target zone. It’s a big advantage for complicated exploration zone.

Conclusions

The ISS IMA method is modified and improved by identifying certain multiple generators to remove target internal multiples in the reservoir. This modification can reduce computational cost and improve efficiency of internal multiple prediction and removal. The modified IMA method still contains the merit of the previous IMA method. It is data-driven and can predict internal multiples without requiring subsurface information and user intervention. Especially, the modified IMA method provides added value for attenuating the target internal multiples and it can predict and remove the target internal multiples for certain identified generators in the target reservoir. The synthetic tests show that the modified IMA method can remove the target internal multiples step by step for each generator separately. It’s very useful for removing certain target internal multiples that are interfering with or proximal to primaries in the reservoir. Field data examples show that the modified IMA method can remove effectively and successfully the target internal multiples and is better than other internal multiple removal methods. In sum, the synthetic and field data tests prove the availability of the modified IMA method and show its advantage for the target internal multiple removal for complicated target zone.

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Figure 1 The synthetic data (a); The internal multiples prediction (b) and (c) removal for generator 1; The internal multiples prediction (d) and removal (e) for generator 2. Figures in the right column are their corresponding trace plots.

Figure 2 The synthetic data with noise (a); The internal multiples prediction (b) and (c) removal for generator 1; The internal multiples prediction (d) and removal (e) for generator 2. Figures in the right column are their corresponding trace plots.
Figure 3 Field data 1 (a); After internal multiples removal by using other method (b) and the modified IMA method (c).

Figure 4 Field data 2 (a); After internal multiples removal by using other method (b) and the modified IMA algorithm (c).

References


