Seismic multiple attenuation based on pre-stack reflectivity modelling

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SUMMARY

A particular method of pre-stack multiple attenuation, based on generalised linear inversion (GLI) and the Haskell-matrix formulation, is investigated. The method uses GLI to obtain a 2-D earth-reflectivity function which produces a synthetic seismic record as close as possible to the observed seismic data. The forward model employs the Haskell-matrix method to compute the entire elastic response, including primaries and multiples, corresponding to an input reflectivity. The final reflectivity is used to generate a multiples-only signal, which is subtracted from the original.

Initial trials have been carried out on noisy synthetic pre-stack gathers. Despite erroneous starting earth models, the inversion iterates robustly to provide an output record exhibiting excellent agreement with the observed record. This leads to effective multiple attenuation.

The Haskell matrix method is naturally formulated in terms of wave slowness, and hence the inversion algorithm is most conveniently carried out in either the τ–p domain, or the *f-p* domain. Our experimentation suggests that, in the presence of noise, the *f-p* domain is more robust than τ–p.

This method is computationally more expensive than conventional multiple removal strategies, such as those based on differential moveout or predictive deconvolution. Hence it is likely to have most potential where these approaches fail.

Key words: multiple attenuation, generalised linear inversion, reflectivity modelling.

INTRODUCTION

Multiple interference continues to be a serious problem in the field of seismic exploration. Multiple events can be confused for primary reflections, and can otherwise complicate the task of interpretation by distorting primary events.

Conventional multiple attenuation methods tend to fall into two main categories. The first group takes advantage of the different moveout of multiple reflections compared to primary reflections at the same time position. Such methods range from straight CMP stacking with or without inside-trace muting, through to algorithms based on partial moveout followed by muting in the *f-k* or τ-p domain (e.g. Hatton et al., 1986). Another variation involves stacking the data with a moveout which reinforces multiples, and then subtracting this multiple-rich section from the full-response section (e.g. Michon et al., 1971). However, any such method based on differential moveout will tend to fail in circumstances where the offset range is small in comparison to the depth of the geological features of interest.

The second conventional approach to multiple-attenuation, based on the statistical predictability of multiple energy, is predictive deconvolution (e.g. Robinson and Treitel, 1980). Although this method may work well for short-period multiples, it is often unsuccessful for very long period multiples. Hatton et al. (1986) suggest this may be due to the poor preservation of the ratio of the amplitude of the multiple energy to the amplitude of the corresponding primaries. Additionally, predictive deconvolution is based on the assumption that the earth's reflectivity is a random function of time. In some cases this is an erroneous assumption (e.g. Walden and Hosken, 1985; Phythian et al., 1995).

A variety of alternative multiple-suppression algorithms have been suggested over the past two decades. Some of these focus on surface-related multiples (e.g. Verschuur, 1992; Dragoset and Jericevic, 1998; Ikelle and Guo, 1998). Other methods aim specifically at removing water-bottom multiple energy (Carrion, 1986; Hinds and Durrheim, 1998; Lu et al, 1999). Foster and Mosher (1992) have demonstrated a hyperbolic τ-p transform approach that performs better than the more conventional parabolic approach. Karanzincir (1999) has described a subtractive method which uses simulated-annealing optimisation to model observed reflection data.

In this paper we examine a subtractive multiple-attenuation method which uses generalised linear inversion to find an earth model consistent with the observed pre-stack seismic record. The inversion phase has similarities to the work of McAuley (1985, 1986). The current paper is restricted to basic theory and issues relating to stable model inversion. Several significant practical issues will need subsequent attention for viable production use. The current investigation is driven by a particular problem relating to severe interbed multiples, which is difficult to treat with other approaches. However, the concept should be more generally applicable.

INVERSION ALGORITHM

To compute a synthetic seismic response of the earth we use the layer-matrix algorithm originally due to Haskell (1952, 1963), and recast in Z-transform terminology by Frasier (1970). This produces the full P- and S-wave reflection response of the earth, including primaries and multiples. The method is conveniently implemented in terms of constant slowness traces rather than constant offset traces, so our modelling is carried out in the τ-p domain. The resultant full-band Haskell-matrix response is convolved with an appropriate wavelet, which may be found deterministically from the observed seismic record, or as part of the generalised linear inversion process.

Generalised linear inversion is used to attempt to match the observed seismic response with the output from the reflectivity modelling scheme described above. This involves adjusting the earth model used by the reflectivity-modelling process in an iterative fashion, until the following objective function is minimised:

$$\gamma = \sum_{i=p_{\min}}^{p_{\max}} \sum_{j=\tau_{\min}}^{\tau_{\max}} \left| s_{ij} - f_{ij}(\mathbf{m}) \right|^2 \quad , \qquad (1)$$

where s_{ij} is the observed seismic trace at slowness i and intercept time j, and $f_{ij}(\mathbf{m})$ is the modelled seismic trace at slowness i and intercept time j, constructed for model parameters **m**.

The earth-model parameters (**m**) required to initiate this inversion process can be recovered from conventional seismic trace inversion of the observed small-offset traces, or from nearby well log data. In defining the earth model for this inversion process we have assumed that the P-wave velocity, S-wave velocity and density of the earth are functions of depth only. This is tantamount to assuming that, in the vicinity of the pre-stack shot record being analysed, the earth consists of homogenous horizontal layers. In cases where the geology is expected to be relatively simple, with only a few significant reflecting horizons, it may be useful to assume there is a relationship between P-wave velocity, S-wave velocity and density. This will reduce the number of parameters required to define the earth model, and so help stabilise the inversion process used to produce the modelled seismic record. Once the optimum earth model is found, it can be used to calculate a multiples-only seismic record. This estimate of the multiple wavefield is used to attenuate multiple energy in the observed seismic record by subtraction.

SYNTHETIC EXAMPLE

Here we illustrate the concept with reference to a simple coal-scale numerical example. Figure 1 shows a noisy synthetic 'observed' pre-stack record. Strong multiple energy exists towards the later part of the record (> 0.28 s). The initial earth-model was chosen to be very inaccurate, and hence the corresponding pre-stack record (Figure 2) differs significantly from the observed record. This initial guess of the earth model was passed through 12 iterations of our inversion technique. The final earth model produced by this iteration process gave a shot record that matches the observed record very well (Figure 3). The difference record between this final record, and the observed record, contains only noise.

The final earth model estimate was used to generate a multiples-only record, which was subtracted from the observed data. Figure 4 shows that the strong multiple energy towards the latter part of the record has been attenuated, revealing weaker underlying primary reflections.

COMMENTS

The inversion process is computationally expensive. As part of the process, three full synthetic seismic records must be generated for every input parameter, once per iteration. A typical record with noise may take ten to twenty iterations to invert satisfactorily. The algorithm does, however, lend itself to parallelisation. In addition, we have found that significant computational savings can be made if the input and output models are parameterised in the frequency domain for the purposes of inversion.

Interestingly, there are cases where the modelled output and observed signal match well enough to allow successful multiple attenuation, even when the estimate of layer parameters is imperfect. This is due to non-uniqueness, with more than one set of model parameters able to produce the required output. Hence the process of multiple estimation and removal may be more viable than the actual recovery of an accurate earth model.

CONCLUSION

We have examined the feasibility of applying generalised linear inversion, using Haskell-matrix modelling, to the task of attenuating multiple energy in seismic data. Initial trials on noisy synthetic pre-stack records have produced robust inversions, even for inaccurate starting models. The technique is computationally expensive and a number of practical issues are yet to be addressed. However the concept may have future potential in geological situations where existing multiple-attenuation techniques prove inadequate.

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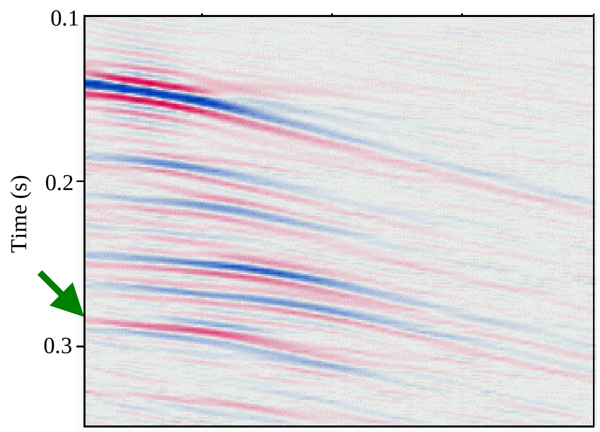

Figure 1. 'Observed' noisy pre-stack gather. In this coal-scale example the maximum offset is 400m.

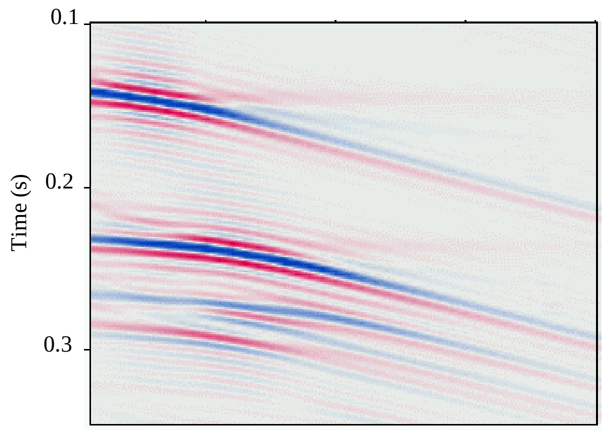

Figure 2. Initial synthetic record corresponding to the initial, erroneous earth model.

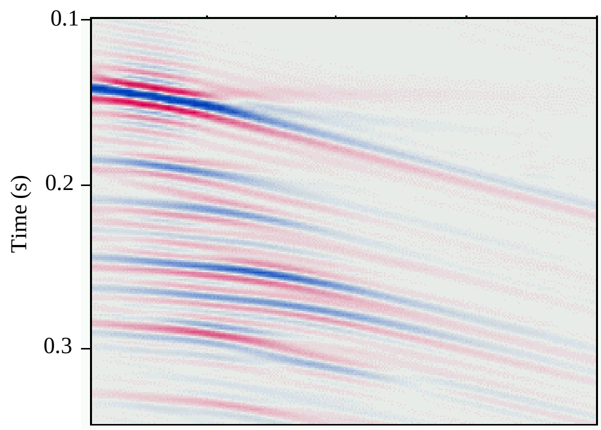

Figure 3. Final output from the generalised linear inversion process. Compare with observed record of Figure 1.

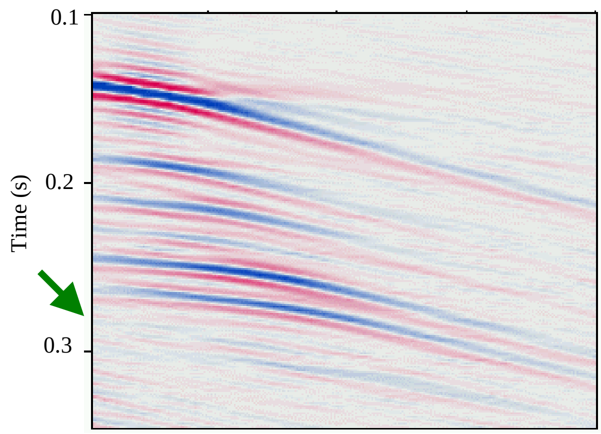

Figure 4. Original record with multiple energy attenuated. Compare with Figure 1.