Practical evaluation of P- and S-wave separation via elastic wavefield decomposition

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SUMMARY

Compressional (P) and shear (S) waves respond differently to the Earth's geology. Hence an integrated interpretation of multi-component seismic data should provide greater information about the sub-surface than is available from P-wave data alone. Conventional multi-component seismic analysis uses scalar component selection to provide P- and S-wave images. This approach has proven successful in many situations. However, where P energy contaminates the horizontal components, and S energy contaminates the vertical component, there is potential to achieve purer P- and S-wave records by more fully exploiting the true vector nature of multi-component seismic data.

One elegant vector-processing technique, here referred to as elastic wavefield decomposition (EWD), takes advantage of the P- and S-wave separation properties of the divergence and curl operators. Practical implementation of EWD requires information about the seismic wavefield at depth. This is achieved via downward continuation of the elastic data in the time domain via a finite-difference approach.

Synthetic and real onshore multi-component seismic data are used to evaluate the practical viability of EWD for real-data applications. The robustness of the wavefield separation is dependent on the accuracy and smoothness of the velocity model used during the downward continuation stage of the algorithm. Velocity errors of up to 10% can be tolerated, after which significant artefacts appear in the separated records. A smooth velocity model will avoid contamination by spurious reflection events. P/S separation is still effective where a constant velocity model is used for data suffering from statics associated with lateral inhomogeneities in the near surface. Moderate noise contamination does not seem to significantly impact on the wavefield separation results. In fact, the downward continuation process appears to suppress random noise. Application of EWD to a real two-component record appears to enhance the relative strength and coherency of the P- and S-wave reflection events in the extracted P and S records.

Key words: Elastic wavefield decomposition, vector processing, multi-component, P- and S-wave separation

INTRODUCTION

There now exist a number of examples in which multi-component seismic imaging has considerably enhanced exploration (eg, Kendall *et al*, 1998; Barkved *et al*, 1999; MacLeod *et al*, 1999). Typically, the P-wave image is produced via scalar processing of the vertical component, and the corresponding converted-wave (PS) image is obtained from scalar processing of the horizontal component(s). This conventional component-selection approach ignores the potential cross-contamination of P-wave energy on to the horizontal components, and S-wave energy on to the vertical component. Basic ray-parameter concepts dictate that such cross-contamination is likely to be observed in areas with relatively high-velocity surface layers (eg, areas with surface basalts and/or limestone reefs).

True vector-processing techniques take advantage of the actual wavefield particle motion to distinguish between wave types, and have the potential to produce cleaner P- and S-wave records in areas prone to significant wavefield cross-contamination. Vector techniques include those that operate in the *f-k* or *τ-p* domain (eg, Greenhalgh *et al*, 1990; Donati and Stewart, 1996), and those based on frequency-domain parametric equations (eg, Leaney, 1990; Cho 1991; Hendrick and Hearn, 2003). Some of these methods are not well suited to production processing (Hendrick, 2001). Here we examine an alternative approach based on the mathematical divergence and curl operators (eg, Sun, 1999). This algorithm, referred to here as elastic wavefield decomposition (EWD), has received some attention in recent geophysical literature (eg, Sun *et al*, 2001; Sun *et al*, 2004). However, to date, no real-data examples demonstrating P/S separation via EWD have been described. This paper examines the practical viability of EWD for real-data applications. A number of synthetic trials, each addressing real-data issues such as velocity models, noise and statics, are discussed. EWD is also evaluated on a real two-component seismic shot record.

ELASTIC WAVEFIELD DECOMPOSITION (EWD)

The equation of motion that describes the propagation of stresses through a medium is given, in terms of displacements, by:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = (\lambda + \mu)\nabla\theta + \mu\nabla^2\mathbf{u} \,, \qquad (1)$$

where $\mathbf{u} = (u_x, u_z)$ is the vector of horizontal and vertical displacements recorded over time (t) in the two-dimensional plane defined by the horizontal and vertical spatial coordinates x and z, $\theta = \nabla\cdot\mathbf{u}$ is dilatation, ρ is density, and μ and λ are the Lamé constants (eg, Grant and West, 1965).

Application of the divergence and curl operators to Equation (1) yields separate equations for the propagation of P and S waves, respectively. In these equations the propagating entities are the dilatation:

$$\theta = \nabla\cdot\mathbf{u} = \frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z} \,, \qquad (2)$$

and rotation:

$$\varphi = \nabla \times \mathbf{u} = \frac{\partial u_x}{\partial z} - \frac{\partial u_z}{\partial x}. \quad (3)$$

It follows that application of the divergence operator (∇·) to a multi-component seismic record will effectively recover P energy from the vector data, while the curl operator (∇×) will recover S energy.

In order to recover P- and S-wave records via Equations (2) and (3), the spatial derivatives of the recorded displacement data with respect to x and z must be computed. Since only surface recorded data are typically available for seismic exploration applications, it is necessary to determine additional information about the wavefield at depth to enable computation of the vertical derivatives. Here downward continuation of the elastic data in the time domain via a finite-difference approach is used to extract seismic displacement at depth. This follows the examples of Sun (1999) and Zhe and Greenhalgh (1997).

Downward continuation of surface vector data can be considered the inverse of elastic forward modelling. In this study an explicit 2nd-order time and 4th-order space finite-difference scheme is implemented to perform the downward continuation. In order to drive the reverse-time propagation, the vertical and horizontal components of the input seismic record are inserted as time-varying surface boundary conditions on the vertical-component and horizontal-component finite-difference grids, respectively (Sun and McMechan, 1986). To initiate the reverse-time recursion process, it is assumed that beyond the maximum time of recording there is no significant energy. To prevent artificial reflections from the bottom and sides of the finite-difference grids during downward continuation, the absorbing boundary conditions of Cerjan *et al* (1985) have been implemented.

Note that the spatial derivatives in Equations (2) and (3) introduce a π/2 phase shift between the input displacement data and the output dilatation and rotation. Sun *et al* (2001) demonstrate that this phase shift can be corrected by performing a Hilbert transform with respect to time on the separated P and S records. Note that, for real seismic data, we are typically working with velocity rather than displacement data. In this instance, the displacement, dilatation and rotation in Equations (1) to (3) should be replaced with their individual time derivatives. The phase correction still remains valid.

Figure 1 shows a simple two-dimensional Earth model and the corresponding two-component synthetic record that has been used as a basis for testing EWD. There is significant cross-contamination of P energy on the horizontal component, and S energy on the vertical component. Figure 2 shows the result of downward continuing the surface vector records to a depth of 10 m, and the corresponding P- and S-wave records produced by application of the divergence and curl operators. The records extracted by EWD are purer P- and S-wave records than the vertical- and horizontal-component seismic records, respectively. Cross-contaminating events have been eliminated.

PRACTICAL IMPLEMENTATION ISSUES

As a prelude to our real-data trials we have modelled a number of issues relevant to practical implementation of EWD.

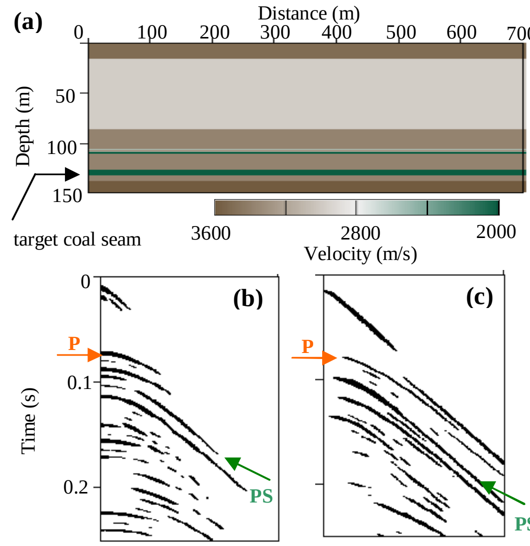

Figure 1. A simple coal-scale Earth model (a) has been used to generate the vertical (b) and horizontal (c) component seismic records for testing of EWD. A high-velocity surface layer is incorporated to accentuate P/S cross-contamination for the purpose of demonstrating vector processing. The source is explosive and is located at (x, z) = (100 m, 20 m). The source wavelet is a derivative of a Gaussian function and has a dominant frequency of 90 Hz. The receiver spacing is 2.5 m and the maximum offset is 500 m. The target P and PS reflection events are indicated.

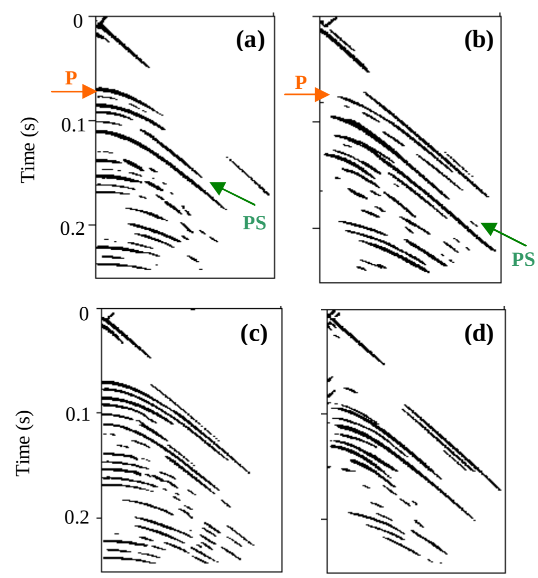

Figure 2. The two-component synthetic record in Figure 1 has been downward continued to produce the vertical (a) and horizontal (b) seismic records at a depth of 10 m. A constant velocity model of Vp = 3500 m/s and Vs = 2005 m/s has been used for the downward continuation. The target P and PS reflection events are indicated. Application of the divergence operator to these downward continued records produces the P-wave record shown in (c). Application of the curl operator produces the S-wave record shown in (d).

Optimum Velocity Model and Continuation Depth

The robustness of EWD is affected by the accuracy and smoothness of the velocity model used for downward continuation. Firstly, an inaccurate velocity model results in individual seismic events propagating differently on the vertical and horizontal components during downward continuation. This misalignment degrades the subsequent wavefield decomposition. Our experiments indicate that velocity errors of up to 10% can generally be tolerated, after which significant artefacts appear in the separated records.

While an accurate velocity model is desirable, there is a practical disadvantage in using a model containing sharp discontinuities. During the downward continuation process such discontinuities will be the source of spurious P and PS reflection events. A constant-velocity model does not produce such artefacts, but may be sufficiently inaccurate in places to yield the misalignment errors discussed above. One compromise is to incorporate smooth variations in the required velocity model.

Downward continuation of the data is required primarily to provide vertical spatial derivatives for computing the dilatation and rotation (Equations (2) and (3)). In this context, only a shallow continuation is needed. This is attractive in terms of computational effort and numerical stability. Our standard approach then is to use a shallow continuation depth and a constant velocity model. One motive for using a larger continuation depth has been indicated by McMechan and Sun (1991), who demonstrated that downward-continuation can attenuate coherent seismic noise (eg, direct waves, ground roll). These events are accommodated in the elastic wave equation. Hence when the data are projected below the depth at which such noise propagates, the noise should be eliminated. Our synthetic and real-data trials confirm this concept.

Static Errors

McMechan and Chen (1990) suggest that static errors can be potentially corrected by downward continuation of surface data to a plane beneath the zone of significant velocity variation. We have verified this concept by analysing finite-difference synthetics constructed from models incorporating laterally varying near-surface velocities. P- and S-wavefields extracted by decomposition below the zone of variability exhibit no significant static errors. This result is theoretically impressive.

However, the practical viability of the concept may be limited, since the available velocity model would typically not be accurate enough to allow such static correction. The question then arises as to whether our standard EWD process (using a constant-velocity model and shallow continuation depth) is still viable when static errors are present. Our synthetic tests indicate that the presence of static errors certainly reduces the effectiveness of the decomposition, in comparison to the static-free case. Nevertheless, the process can still yield positive results in terms of cleaner P- and S-wave records.

Non-seismic Noise Contamination

As indicated above, downward continuation may have relevance for attenuation of surface-related seismic noise. Chen and Chang (2001) have further suggested that downward continuation may also have benefit in reducing non-seismic noise events. Our synthetic tests confirm that the procedure does indeed provide attenuation of random noise, although there is some tendency to introduce weaker, linear noise events as the signal-to-noise ratio drops significantly. The real-data trial included below illustrates the ability of the continuation process to attenuate random noise. On the other hand, our tests do not indicate any consistent attenuation of non-seismic coherent noise.

REAL-DATA TRIAL

Figures 3(a) and 3(b) show the raw vertical and inline components of a shot record from a recent multi-component survey in the Bowen Basin, Australia (Velseis, 2003). On the vertical component the P-wave reflection from the target coal seam is at 0.1 s at zero offset. The inline component shows the corresponding target PS reflection event (0.2 s – 0.25 s on centre traces). Ground roll occurs on both components, and there is significant random noise.

Figures 3(c) and 3(d) show the data following downward continuation to 12 m. The downward continuation has provided significant attenuation of the random noise. Consequently the seismic events have become more coherent. In particular, it is now apparent that the vertical record (Figure 3(c)) is cross-contaminated by the target PS reflection energy (0.2 s – 0.25 s on centre traces).

Figures 3(e) and 3(f) show the P- and S-wavefields extracted via application of the divergence and curl operators. (These should be compared with Figures 3(c) and 3(d), respectively.) On the P-wave record (Figure 3(e)) the main target reflector has been considerably enhanced relative to other energy. In particular, both the ground roll energy and the contaminating PS conversion have been attenuated. Similarly on the extracted S-wavefield (Figure 3(f)), the target PS event has been enhanced relative to other energy. Additionally, there is now evidence of other coherent S-wave energy, possibly resulting from conversions at shallower interfaces (eg, around 0.15 s, centre traces).

CONCLUSIONS

True vector-processing schemes that exploit the particle-motion information inherent in multi-component data have the potential to produce clean P- and S-wave records where there is significant cross-contamination of P and S energy on to the horizontal and vertical components, respectively. EWD is an elegant vector-processing technique that takes advantage of the P and S separation properties of the divergence and curl operators. Practical implementation of EWD involves downward continuation of the surface-recorded vector data and requires a near-surface velocity model. Moderate errors in the velocity model can be tolerated, and the best approach is to assume a constant velocity. Shallow continuation depths are preferred in order to reduce computational effort and minimise the potential for numerical noise. EWD is capable of operating in the presence of coherent and random noise, and will yield positive results when data suffer from static errors. Real-data trials illustrate that EWD can enhance the relative strength and coherency of P and S reflection events, while suppressing any wavefield cross-contamination and random noise. This research has demonstrated that EWD is practically robust and efficient, and further testing on a full multi-component seismic dataset is warranted.

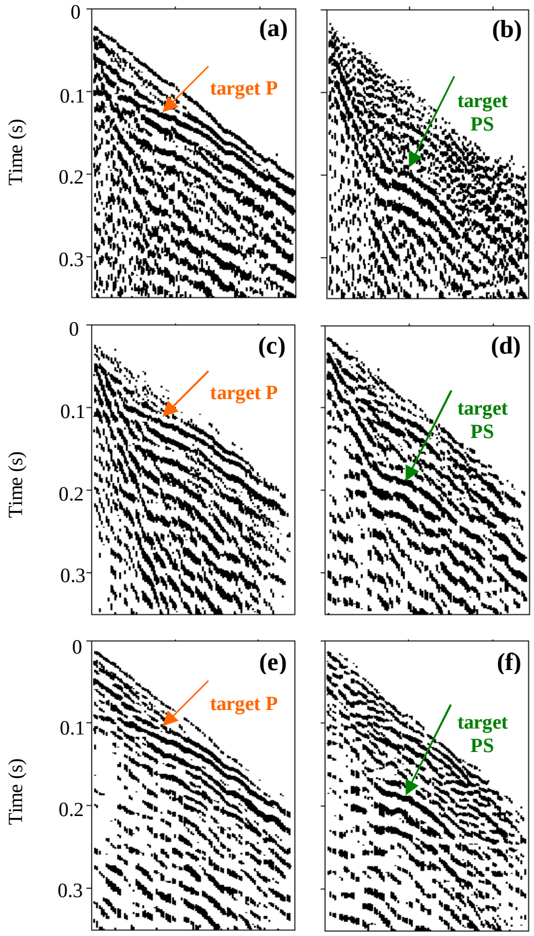

Figure 3. (a) Vertical and (b) inline components of a real multi-component shot record acquired in the Bowen Basin, Australia. The receiver spacing is 5 m and the maximum offset is 600 m. The target P and PS reflection events are indicated. (c) Vertical and (d) inline components of the shot record following downward continuation to a depth of 12 m. A constant velocity model of Vp = 1400 m/s and Vs = 700 m/s has been used for downward continuation. (e) Separated P-wave record and (f) separated S-wave record produced via application of the divergence and curl operators, respectively, to the downward continued records.

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