Complex seismic trace analysis and its application to time-lapse seismic surveys

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Summary

Complex trace analysis effects a natural separation of amplitude from angle and allows definition of instantaneous attributes. The instantaneous amplitude defines single lobes for individual wavelets and, along with the instantaneous phase and frequency, has more power to resolve reflectors than trace amplitudes. In the case of strongly overlapping wavelets, the instantaneous amplitude and frequency have characteristics that help identify and distinguish wavelet interference. The instantaneous frequency, a measure of most energy-loaded or center frequency, traces frequency change with time. In time-lapse seismic surveys, the power of resolution and wavelet interference differentiation improves event picks and calculation of time shift and amplitude variation, and the representation of frequency facilitates the study of attenuation.

Introduction

In reservoir monitoring, the velocities, acoustic impedance and attenuation (anelasticity or Q factor) of reservoir rocks can change in response to changes in fluid saturation, pressure, temperature, porosity, etc., due to production or injection. These changes may be detected in time-lapse seismic surveys, depending on the ability to identify and resolve subtle waveform characteristics, which are measured by seismic attributes. Conventional seismic attributes are based on the real seismic trace. Event picks and calculation of time shift and amplitude variation may be difficult or inaccurate due to wavelet interference. Complex trace analysis provides a new way to examining the seismic trace. It treats the seismic trace as the real part of a complex trace, whose imaginary part is the negative Hilbert transform of the real part. This process yields a natural separation of amplitude from angle and enables calculation of instantaneous seismic attributes (Farnbach, 1975; Taner et al., 1979). The instantaneous amplitude combined with instantaneous phase and frequency improves resolution, and hence seismic events from the reservoir top and bottom are more clearly defined. Instantaneous attributes form patterns of change that can identify and distinguish subtle wavelet interference. Instantaneous frequency at the maximum of instantaneous amplitude for a single reflector can be used instead of the Fourier transform to represent dominant frequency and then to trace frequency change with time (Bodine, 1984; Partyka, 2000).

Definition and calculation of the complex seismic trace model

The complex seismic trace can be defined as:

$$\psi(t) = A(t)\,\{\cos[\theta(t)] + i\sin[\theta(t)]\}$$

or

$$\psi(t) = A(t)\,e^{i\theta(t)} \qquad (1)$$

where $f(t) = A(t)\cos[\theta(t)]$, the real part of the complex trace, is the seismic trace we measure from surface seismic surveys, $h(t) = A(t)\sin[\theta(t)]$ is the imaginary part. $A(t)$, $\theta(t)$ and $1/2\pi\ d\theta(t)/dt$ are defined as instantaneous amplitude, instantaneous phase and instantaneous frequency respectively. Note from equation (1) that the imaginary part lags behind the real part by 90^0, and thus it can be found by 90^0 shifting the frequency spectrum of the real part and performing an inverse Fourier transform. This is equivalent to the negative of the Hilbert transform. Hence, the complex trace can be expressed as:

$$\psi(t) = f(t) + ih(t)$$

$$= f(t) - if_{hi}(t) \qquad (2)$$

where $f_{hi}(t)$ denotes the Hilbert transform of f(t), also termed as the quadrature function of f(t) (Bracewell, 1978). It can be shown that the frequency spectrum of the complex seismic trace [ψ (t)] vanishes for $\omega<0$ and has twice the amplitude and the unchanged phase of the real seismic trace's for $\omega>0$. This results in another way to compute the complex trace, i.e., 1) Fourier transform the real seismic trace; 2) zero the amplitude for negative frequencies and double the amplitude for positive frequencies; 3) inversely Fourier transform.

Physical meaning of instantaneous attributes

For a complex signal $\psi(t)$, we define the signal power $|\psi(t)|^2$ (energy per unit time), the energy spectrum $|T(f)|^2$ (energy per unit frequency, where T(f) is the frequency spectrum of ψ (t), and the signal energy E (Rihaczek, 1968; Grace, 1981). Rayleigh's or Plancherel's or Parseval's theorem (Bracewell, 1978; Grace, 1981; Page, 1952; Sheriff and Geldart, 1995) gives:

$$E = \int_{-\infty}^{+\infty} |\psi(t)|^2 dt$$

$$= \int_{-\infty}^{+\infty} |T(f)|^2 df \qquad (3)$$

It can be proven that the signal power at time t is distributed through all frequencies:

$$|\psi(t)|^2 = \int_{-\infty}^{+\infty} \psi(t) T(f)^* e^{-i2\pi ft} df \qquad (4)$$

$$or \ |\psi(t)|^2 = \int_{-\infty}^{+\infty} \psi(t)^* T(f) e^{i2\pi ft} df \qquad (5)$$

The integrands in (4) and (5) can be defined as the signal power density d(t,f). $\psi(t)\, T(f)^* e^{-i2\pi ft}$ in (4) is Rihaczek's complex energy density (Rihaczek, 1968) and $\psi(t)^* T(f) e^{i2\pi ft}$ in (5) is termed as the complex instantaneous power spectrum by Levin (1964). They are the complex conjugates and the choice is immaterial since only the real part of the integral is considered. As a logic extension, we can find a frequency, where the signal power is most concentrated, i.e., energy-weighted average frequency:

$$f = \frac{\int_{-\infty}^{+\infty} f d(t,f) df}{\int_{-\infty}^{+\infty} d(t,f) df} \qquad (6)$$

Since the real part is only considered, equation (6) can be reorganized, by substituting (4) and (2), as:

$$f = \mathrm{Re}\{\frac{\int_{-\infty}^{+\infty} f d(t,f) df}{\int_{-\infty}^{+\infty} d(t,f) df}\}$$

$$= \mathrm{Re}\{\frac{\psi(t) \int_{-\infty}^{+\infty} f T(f)^* e^{-i2\pi ft} df}{\psi(t) \int_{-\infty}^{+\infty} T(f)^* e^{-i2\pi ft} df}\}$$

$$= \mathrm{Re}\{\frac{1}{-2\pi i} \frac{\psi(t) d(\int_{-\infty}^{+\infty} T(f)^* e^{-i2\pi ft} df)/dt}{\psi(t) \int_{-\infty}^{+\infty} T(f)^* e^{-i2\pi ft} df}\}$$

$$= \mathrm{Re}\{\frac{i}{2\pi} \frac{\psi(t) d\psi(t)^* / dt}{\psi(t)\psi(t)^*}\}$$

$$= \mathrm{Re}\{\frac{i}{2\pi} \frac{[f(t)+ih(t)][df(t)/dt - idh(t)/dt]}{[f(t)+ih(t)][f(t)-ih(t)]}\}$$

$$= \frac{1}{2\pi} \frac{f(t)dh(t)/dt - h(t)df(t)/dt}{f(t)^2 + h(t)^2}$$

$$= \frac{1}{2\pi} \frac{d\theta(t)}{dt} \qquad (7)$$

The above frequency coincides with the instantaneous frequency we defined previously. So the instantaneous frequency represents the most energy-loaded frequency in the frequency spectrum. Barnes (1993) called (6) the instantaneous center or mean frequency, which is the instantaneous frequency. The instantaneous amplitude and phase defined previously may be viewed as the amplitude and phase of this most energy-loaded, or center, frequency (instantaneous frequency).

Applications to time-lapse seismic survey

The advantage of the complex seismic trace is separation of amplitude from angle, which allows calculation of instantaneous attributes, which contain independent information about the seismic trace. Many authors have applied instantaneous attributes to geophysical data processing and interpretation (Barnes, 1990, 1991, 1992 and 1993; Bodine, 1984; Ha et al., 1991; Farnbach, 1975; Robertson et al., 1984 and 1988; Tanner et al., 1977 and 1979; White, 1991). In this paper, we discuss the ability to resolve wavelet interference and its application to time-lapse seismic surveys. Figure 1 demonstrates a pattern of interference for Ricker wavelets. Even though interfering wavelets (upper and middle) are indistinguishable when they are separated by small time shifts, the pattern of changes in instantaneous amplitude and frequency implies the existence of interfering wavelets. The increase in instantaneous amplitude and the decrease in instantaneous frequency correspond to an increase in time shift, which is due to a decrease in velocity. This characteristic may be useful for thin reservoir layers in time-lapse seismic surveys. In comparison, amplitude changes in the conventional seismic trace are more difficult to interpret due to tuning effects. As shown in the lower part of Figure 1, instantaneous amplitude and frequency are better able to resolve individual wavelets, facilitating the interpretation of changes in time shift and amplitude in time-lapse seismic surveys. In addition, when wavelets are well separated, the instantaneous frequency at the maximum point of instantaneous amplitude (response frequency) represents the dominant frequency of wavelets (30 Hz in our case).

An important method in time-lapse seismic surveys is to pick the events from the top and bottom of a reservoir and to compare time shift and amplitude variations from two or more surveys. In many cases, event picks from the conventional seismic trace may be difficult or inaccurate due to interference. Figure 2 (upper) is a random reflectivity series generated with the Reflect(1, 0.002) command in Matlab, including approximately 10 major reflectors with a reservoir assumed located between the third and fourth major reflectors from the right side (around 0.7 and 0.74 second). Figure 2 (middle) is a conventional seismic trace produced by convolution of the reflectivity series with a Ricker wavelet (30Hz). As shown in Figure 2 (middle), the events overlap and it is difficult to separate them. However, as shown in Figure 2 (lower), the envelope of instantaneous amplitude (red) is capable of distinguishing 10 major reflectors, including the two events from reservoir top and bottom. The instantaneous frequency (green) also helps identify event interference by its sudden change. As a result, a more accurate estimate of time shifts and amplitude changes is achieved.

Conclusions

Complex trace analysis enables separation of amplitude from angle and definition of independent instantaneous attributes, which are useful in the identification and resolution of individual wavelets. As a result, event picks and calculation of time shifts and amplitude variations can be improved in time-lapse seismic surveys. The instantaneous frequency can be used to monitor frequency change with reflection time, facilitating the study of changes in attenuation.

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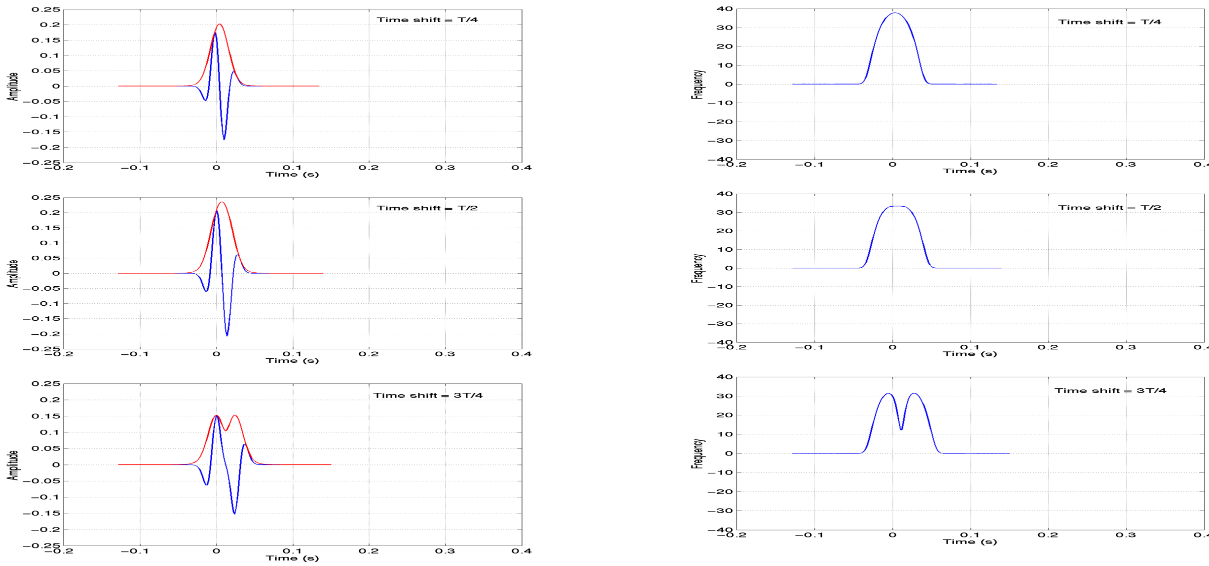

Figure 1 Interfering opposite-polarity Ricker wavelets spaced by T/4, T/2 and 3T/4 (1/T is the dominant frequency, 30 Hz) and the respective diagrams of instantaneous amplitude (left, red) and frequency (right, blue).

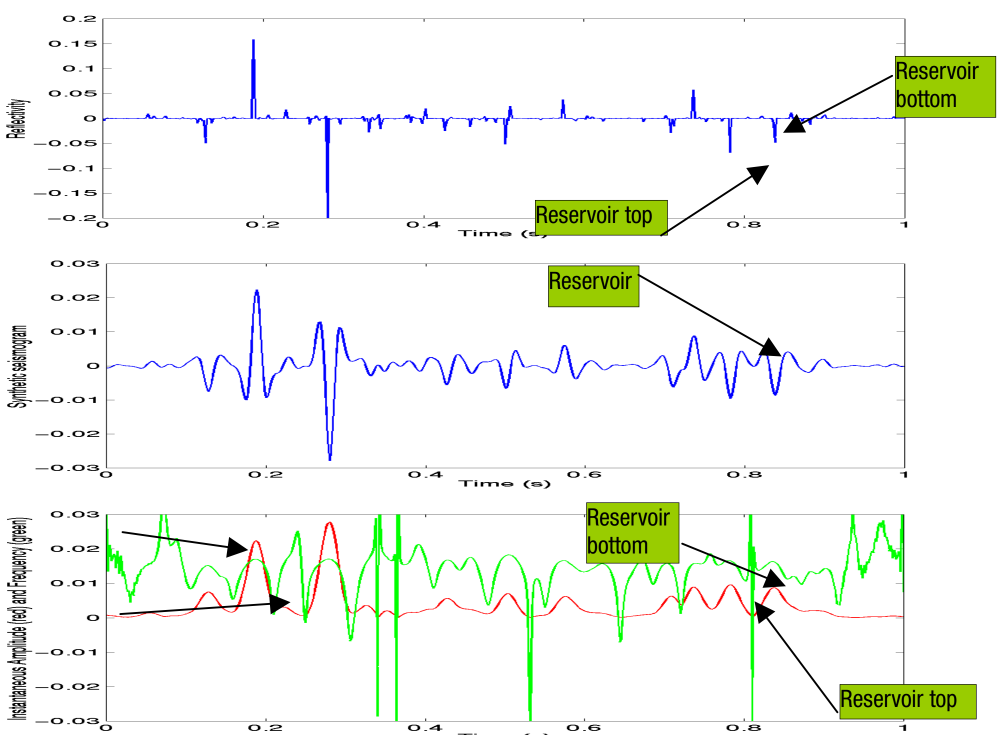

Figure 2 Upper: random reflectivity series generated from Matlab command Reflect(1, 0.002); Middle: synthetic seismogram generated from convolution of the random reflectivity series(Figure1) with the Ricker wavelet (30Hz); Lower: instantaneous amplitude (red) and instantaneous frequency (green, *2000).