Enhancing Seismic Insight by Spectral Decomposition*

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Abstract

Spectral Decomposition is a novel technology developed in recent years. It has proved to be very useful for seismic data interpretation, because decomposing data into its spectral components reveals stratigraphic and structural details that are often obscured in the broadband data. Most popularly utilized spectral decomposition methods include Short windowed Fourier transform (SWFT) (Partyka et al., 1999), Morlet wavelet based wavelet transform (MWT) (Miao and Moon 1994; Casatagna et al., 2003), and Matching Pursuit Decomposition (MPD) (Miao and Cheadle 1998). SWFT involves explicit use of windows, which affects temporal and spectral resolution. Wave-package-like spectral decomposition even though provides better spectral resolution but reduces temporal resolution, which is undesirable for thin bed interpretation. In this paper, in addition to the previously discussed WT and MPD methods, we introduce a generalized Stransform (ST) based spectral decomposition method. We explore the merits and disadvantages of the methods, and apply them to real data to show the interpretive benefits of spectral decomposition.

Methodology

Morlet Wavelet Transform

The Morlet wavelet is a modulated Gaussian function, which is a non-orthogonal compactly supported complex wavelet, although it has side lobes. The decomposition of the MWT is represented in the scale (or voice) and time domain (Miao and Moon 1994). Since scale is related to frequency, we can convert the MWT representation into the frequency-time domain and use it for spectral decomposition. The wavelet transform spectral decomposition has an implicitly defined analysis window, thus without the tapering effects inherent to the more commonly used short window Fourier method.

S-Transform

The S-transform is proposed by Stockwell et al., 1996 as an extension to the Morlet wavelet transform. The mother wavelet for S-transform is also a modulated Gaussian function, but it keeps the modulation part with no scaling and no shifting. The S-transform is then defined as:

$$s(\tau, f) = \int_{-\infty}^{\infty} D(t) g_f(t-\tau) \exp(-i2\pi ft) dt.$$

Where $g_f(t)$ is a Gaussian function given by $g_{\mathrm{f}}(t) = \frac{|f|}{\sqrt{2\pi}} \exp(-(ft)^2)$ and D(t) is the signal. With a small modification to $g_f(t)$:

$$g_{\mathrm{f}}(t) = A|f| \exp(-\alpha(ft-\beta)^2,$$

The S-transform becomes the generalized S-transform. Here A, α and β are constants introduced to add a variety of forms in the mother wavelet so it can better correlate with signals. It directly decomposes signals into the frequency and time domains.

Matching Pursuit Decomposition

The Matching Pursuit Decomposition technique is uniquely suited to providing high-resolution time-frequency spectra. It finds a best matched wavelet from a wavelet dictionary - a large collection of wavelets covering the full ranges of time, frequency, scale, and phase index – to represent each component of a signal, and so can enhance the spectral resolution (Miao and Cheadle 1998) without side lobe effects.

A successful spectral decomposition depends on its resolution as well as robustness. Among the above three algorithms, the MPD provides the highest temporal and spectral resolutions simultaneously, however is the most computationally expensive one. Because of its efficiency and good localization to distinguish subtle changes, the MWT algorithm is still commonly used. Using the amplitude component can compensate its side lobe effect. The generalized ST shares most characteristics as the MWT, however gives higher spectral resolution due to variations of mother wavelet. We compared all the methods using synthetic signals, which will be shown in the presentation.

Application for Seismic Data Interpretation

Because the wavelets in the above methods are complex, one can extract information about both the amplitude and phase of the signal being analyzed. The wavelet amplitude is helpful in analyzing attenuations and stratigraphic variation in time and frequency simultaneously, while the wavelet phase is useful in locating discontinuities and identifying fractures.

We have applied spectral decomposition to real seismic data. A successful interpretation application is for SAGD monitoring. While it is difficult to identify locations of horizontal wells with the broadband data, they are more readily distinguished by means of certain iso-frequency cubes because of fixed dimensions of wells. The development of heating flows along the well paths causes frequency dependent spectral attenuations; these can be very well traced in these iso-frequency cubes, so that the steaming quantities are better monitored. In addition, fractures in the steaming zones can also be easily discovered. Examples will be shown in the presentation.

Another excellent application is using the tuning cube for interpretation (Partyka et al., 1999). A tuning cube containing amplitude spectra for a target zone can be created along a horizon. It is used to analyze frequency dependent stratigraphic and structural features as well as to identify the dominant frequency at each cmp location for the examined horizon. Dominant frequency can be calibrated with thickness from well log information, so that the tuning cube portrays estimated thickness of target zones.

Figure 1 shows an example of using tuning cube to estimate relative thickness of channel sands. Dominant frequency estimated from the tuning cube at the target zone is shown in color. Pink and red colors correspond to higher dominant frequencies and thinner sands; blue represents lower frequencies and thicker sands. By overlaying the known thickness of net pay - shown in white contours - one can see excellent alignment of the known thickness with this seismically-predicted thickness indicator.

Conclusions

Spectral decomposition is a powerful tool for seismic data interpretation. By using compactly supported mother wavelets, the MWT, ST, and MPD based spectral decomposition methods provide excellent temporal and spectral resolution. Applications to seismic data interpretation have enhanced our insights to subsurface structural and stratigraphic variations, which will lead to more successful exploration and field development.

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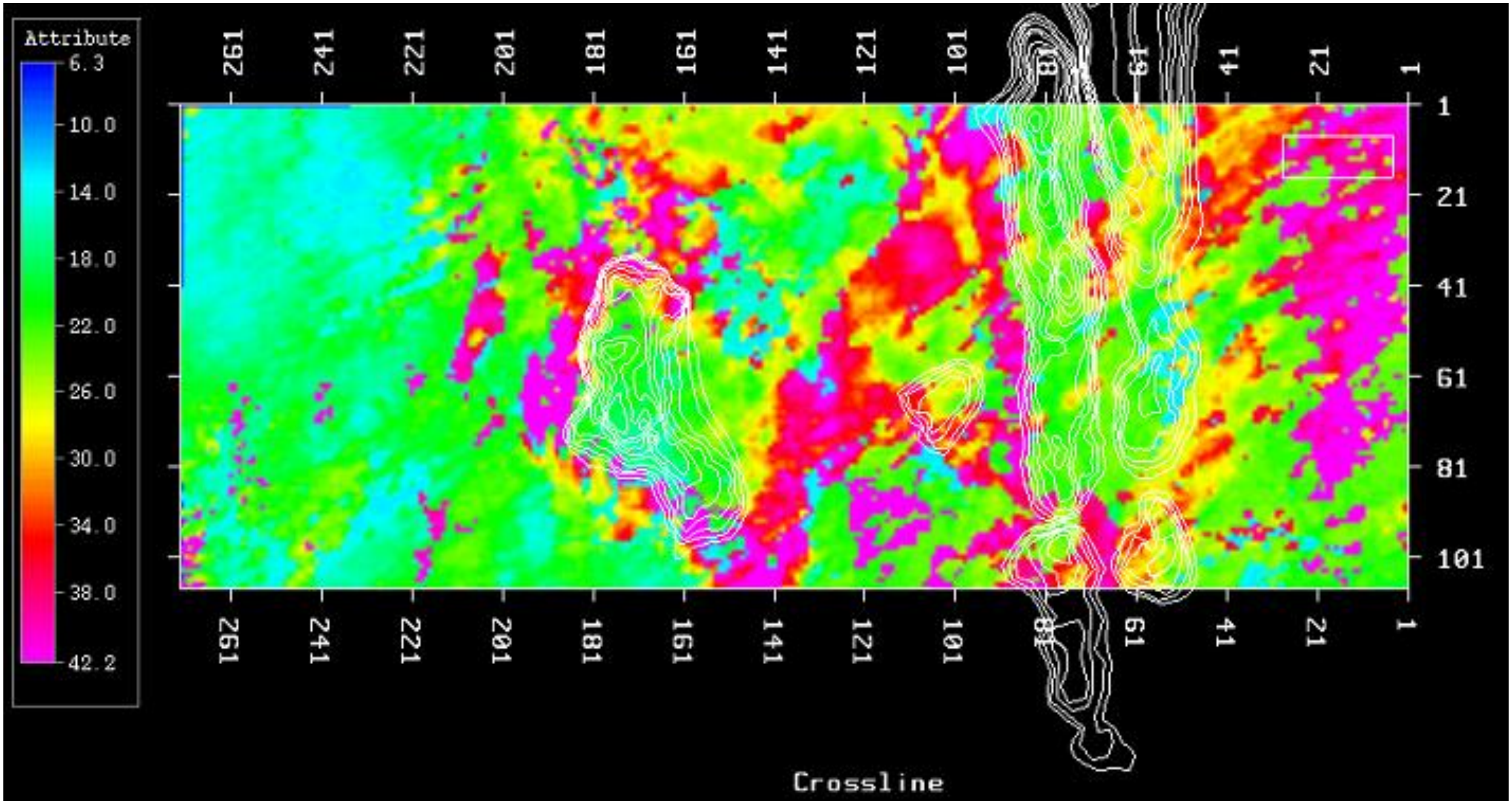

Figure 1. Dominant frequency estimated from the tuning cube for a target zone. The color bar is the dominant frequency in Hz. The white contours represent the known thickness of net pay, which correspond with the red area margins where the reduction of sand thickness occurs.