Does It Matter What Kind of Vibroseis Deconvolution is Used?

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CSEG Geophysics 2002

Summary

Effective seismic interpretation in stratigraphic plays demands that the seismic wavelet in the final section be both constant and of known phase. The transfer function between the vibrator pilot sweep and the far field signature is the response that must be compensated for to arrive at such high quality seismic.

The downgoing wavefield extracted from a Vertical Seismic Profile (VSP) represents the far-field downward travelling signature, sampled at the discrete depths of the geophone stations. Vibroseis deconvolution is based on an attempt to estimate that signature knowing some characteristic of the impulsive system (normally the pilot sweep) and making some assumptions about the statistics of the reflectivity series. Therefore the VSP experiment is the ideal tool to test the effectiveness of the signature estimation tools routinely used for surface seismic reflection data.

A 3-component walk-away VSP survey was conducted at Husky Energy Inc.'s Pikes Peak oilfield in September 2000. Zero-offset (23 m) data were used to analyze the effect of various vibroseis processing strategies on the polarity of the downgoing data. Zero-phase deconvolution and vibroseis minimum phase predictive deconvolution all had some residual phase errors with reference to the hoped for zero phase results. The minimum phase vibroseis deconvolution however appeared to offer some improvements over zero-phase deconvolution.

Introduction

Schlumberger Canada conducted the VSP in well 141/15-06-50-23W3M, using their 3-component, 5-level ASI tool. A Mertz HD18 Buggy P-wave vibrator, using an eight second 8 to 200 hertz linear sweep, served as the source at zero offset (23 m). The downhole geophones were magnetically clamped to the casing from 514.5 m to 27 m measured from KB at 7.5 m intervals (66 levels). The weighted sum ground force estimate was used as the phase-lock signal. The weighted sum ground force estimate was kept 180 degrees out of phase with the pilot sweep (the SEG polarity standard is to have the weighted sum ground force estimate in phase with the pilot sweep). The pilot sweep was recorded on auxiliary channel 1 and the weighted sum estimate of the ground force was recorded on auxiliary channel 2.

Problems with standard vibroseis theory

Miller and Pursey, 1954 and Aki and Richards, 1980 have shown that the P-wave far-field particle displacement is proportional to the applied force. This relationship of force and far-field particle displacement is often referred to as the 'standard vibroseis theory'. An equivalent statement of the standard theory is that the far-field particle velocity source response is the time derivative of the true ground force. The true ground force is the integration of the pressures beneath the baseplate. The ground force is often estimated by a weighted sum of outputs from two accelerometers placed on the reaction mass and baseplate assemblies. The weighted sum estimation of the ground force is almost universally used as the feedback signal on vibrators today. Baeten and Ziolkowski, 1990 mentions three reasons why correlated vibroseis data does not contain a zero phase wavelet. First, due to smoothing by the vibrator electronics and inaccuracies in the

feedback system of the vibrator, the weighted sum signal differs from the pilot sweep. Second, the far field wavelet is not proportional to the ground force but to its time derivative. Third, due to the bending of the baseplate, the true ground force is not equal to the weighted sum estimate. Sallas, 1985 and Baeten and Ziolkowski, 1990 have shown empirically (figure 1) that the weighted sum estimate of the ground force deviates from the true ground force. They show that when the weighted sum ground force estimate is controlled to be constant the true ground force varies with frequency. The amount of bending of the baseplate will depend on the type of Vibrator and the mechanical properties of the earth immediately below the baseplate. The green curve in figure 1 is the predicted amplitude spectrum of the far field source signature. It was obtained by applying a 6 db per octave boost to the amplitude spectrum of the true ground force from Baeten and Ziolkowski. The far-field source wavelet amplitude spectrum estimate is not flat.
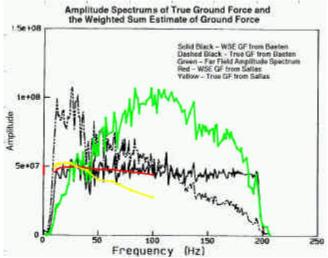

Figure 1: Comparisons of the true ground force and the weighted sum estimate of ground force from Baeten and Sallas

Vibroseis deconvolution theory assumptions

Conventional predictive deconvolution assumes that the reflectivity of the earth is statistically white, the data is noise free, and the seismic wavelet is minimum phase. Using predictive deconvolution on vibroseis data, especially the spiking variety, is clearly a violation of the minimum phase assumption as the source signature is constant phase. Most papers on vibroseis deconvolution begin their discussion by stating that on a correlated vibroseis trace, the seismic wavelet is the convolution of the zero-phase Klauder wavelet with minimum-phase components such as recording instruments, attenuation, ghosts, reverberations and other types of multiple reflections. This mixed-phase input they say is a problem for spiking deconvolution. The usual solution is to convert the Klauder wavelet to its minimum-phase equivalent. The minimum-phase equivalent does not exist if there are zeros in the spectrum of the signal so a small amount of white noise must be added. Three recent papers on vibroseis deconvolution; Cambois, 2000, Robinson and Saggaf, 2001, and Brittle el al, 2001 discuss the problem of finding the minimum-phase equivalent of the cross-correlation of the pilot sweep (the Klauder wavelet). They do not mention any reservations about

assuming that the Klauder wavelet represents the 'vibroseis shot signature'. Wason and Potts, 1984, do mention the time derivative shape of the far field wavelets but state that replacing this wavelet with its minimum-phase equivalent will cause a 90 degree phase change that will result in a zero phase wavelet.

Field Observations

The weighted sum ground force estimate recorded on auxiliary channel 2 crosscorrelated with the ideal sweep and with the impulse response of the instruments and geophones removed (figure 2) shows a very close to 180 degree Klauder wavelet. The amplitude spectrums decrease about 2 db over the sweep range. The vibroseis control system has done a very good job of matching the feedback signal to the ideal sweep. Baeten and Ziolkowski's, 1990 first reason for thinking that the 'vibroseis shot' is not zero-phase is a small problem in this experiment.
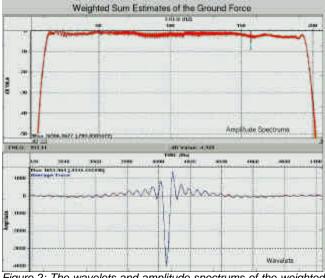

Figure 2: The wavelets and amplitude spectrums of the weighted sum estimates of the ground force

After wave field separation, flattening on the first arrivals, and geophone and instrument impulse response removal, the 66 downgoing wavelets (figure 3) show a shape that is close to 90 degrees up to about 60 hertz. This is expected from the standard theory. Above 60 hertz, the phase of the downgoing wavelets departs substantially from what would be expected from the standard theory. Baeten and Ziolkowski, 1990 (figure 4) have reported a substantial phase difference between the true ground force and the weighted sum ground force that could explain some of this discrepancy.
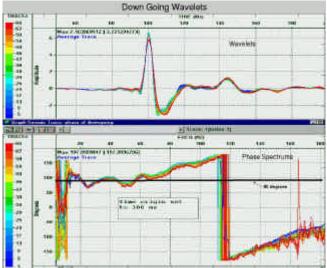

Figure 3: The 66 downgoing wavelets and their phase spectrums after wavefield separation
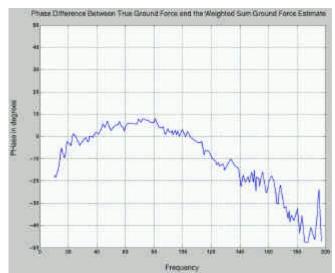

Figure 4: Phase difference reported by Baeten and Ziolkowski, 1990 between the true ground force and the weighted sum estimate of the ground force

The downgoing wavelets have amplitude spectrums that drop off with frequency (figure 5). Three mechanisms: attenuation, reflectivity scattering, and baseplate bending cause this loss of frequency content. The difference in slope between the shallow wavelet amplitude spectrums (blues) and deeper amplitude spectrums (red) is caused by attenuation. Hedlin et al, 2001 have used the spectral ratio method to estimate Q's from this VSP (figure 6). Non-physical negative Q values above 150 meters have not been explained.
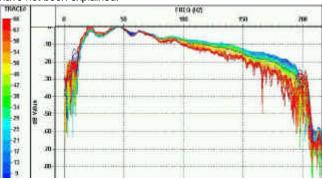

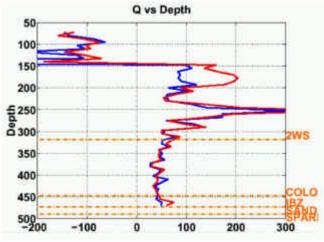*Figure 5: Amplitude Spectrums of the 66 downgoing wavelets*

Figure 6: Q versus Depth calculated from VSP survey. Calculation was done using geophones of 90 m. separation.

Results of deconvolution

Continental Oil Company (the developer of the Vibroseis method) recommended in the 1970's that zero-phase deconvolution be used on vibroseis data. This was quite a popular method untill about the end of the 1980's and is still used on some data with apparently good results. Frequency domain zero-phase deconvolution with 4 hertz smoothing was run on the downgoing wavelets after applying a –90 degree phase shift (figure 7). These wavelets are not zero-phase as the phase shifts measured in figure 3 are still present.
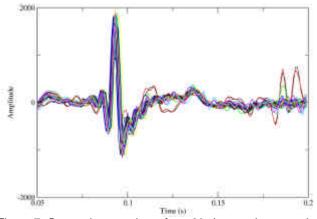

Figure 7: Downgoing wavelets after –90 degree phase rotation and zero-phase deconvolution

A frequency domain vibroseis predictive deconvolution was applied that shaped the input data with the filter required to convert the assumed Klauder wavelet to its minimum-phase equivalent. The amplitude spectrum of the data in this vibroseis deconvolution was amortized at the low frequencies when estimating the phase of the deconvolution operators but left as it was when estimating the deconvolution operator's amplitude spectrums. The vibroseis deconvolution was run with 4 hertz smoothing and low frequences amortized between 0 and 13 hertz on the downgoing wavelets (figure 8). Compared to figure 7, there is a less noisy appearance and the downgoing multiple at about 120 ms is eliminated more completely. The results are still not zero phase.
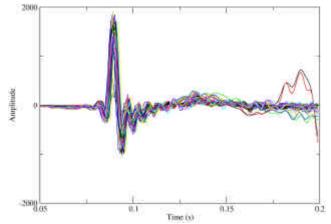

Figure 8: Downgoing wavelets after predictive vibroseis deconvolution in the frequency domain.

Standard vibroseis theory indicates that the far field source signature is the time differential of the true ground force. In figure 7, we assumed that the far field signature was the ideal Klauder wavelet. It would seem better therefore to assume that the true far field source signature is equal to the time differential of the Klauder wavelet. The predictive vibroseis deconvolution was run with a minimum-phase equivalent adjustment for the differentiated Klauder wavelet on the downgoing wavelets (figure 9). These results are much further from zero-phase than in figure 8.
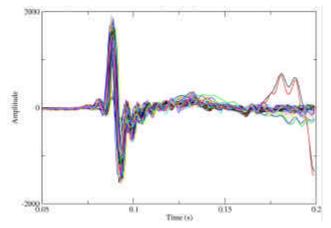

Figure 9: Downgoing wavelets after predictive vibroseis deconvolution with a minimum phase equivalent adjustment for the differentiated Klauder wavelet

Conclusions

Predictive vibroseis deconvolution appears to offer some advantages over zero-phase deconvolution even though it ignores the standard vibroseis theory and its problems. A perfectly zero-phase result from vibroseis deconvolution is not likely. Interpreters should use whatever means are available to them to check the phase of their data.

Acknowledgements

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