Orthogonal sweeps of vibroseis

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Summary

Vibroseis is a method that imparts coded seismic energy into the ground. The energy is recorded with geophones and then processed using the known (coded) input signal. The resulting time-domain representation of vibroseis data is an impulsive wavetrain with wavelet properties consistent with the coded input signal convolved with the earth's reflectivity series. Historically vibratory seismic surveys collect data from one source location at a time summing one or more sources at each location. In this abstract, we present a method of designing orthogonal sweeps using the concept of combisweeps. The orthogonal sweeps allow simultaneous recording and later separation of two (or more) unique source locations. Orthogonality of sweeps permits separation of the data into unique source location field records by a simple correlation procedure. Coincident generation and recording of two vibroseis sweeps at different locations would allow almost double the data recorded for a given occupation time. Simulations suggest separation performance of 33 dB.

Introduction

The use of vibratory sources increases the potential for spectral shaping of the source wavelet, minimizes the environmental impact, and increases the signal-to-noise ratio, while increasing the complexity of in-field and/or post-acquisition processing compared to non-coded impulsive sources. Vibratory techniques were first developed over 30 years ago as an alternate method (non-impulsive) of introducing acoustic energy into the ground (Crawford et al., 1960). This oscillatory energy method, known as "vibroseis," uses a controlled vibrating mass to generate a sinusoidal wavetrain with continuously varying frequency delivered to the ground over a specified time period (Goupillaud, 1976). The sweep (sinusoidal source input function) is correlated/ deconvolved with each time series trace. The record time of each data trace is slightly longer than the sweep (pilot) time to allow sufficient "listen" time for the two-way travel of the entire sweep. The correlation/deconvolution process effectively produces a time series comparable to impulsive source records with respect to full-wave field recording. Historically vibratory seismic surveys have collected data at only one source location at a time. To increase productivity of data acquisition, researchers are working on simultaneously recording signals from multi-vibrators at different locations.

An excellent concept by Allen et al. (1998) demonstrated the 60 dB of separation capability of the high fidelity vibratory seismic (HFVS) method. Wilkinson et al. (1998) applied HFVS method to real data. Their field test indicated a separation performance of approximately 40 dB. We employ the concept of combisweep (Werner and Krey, 1979) to design orthogonal sweeps allowing recording of data from multi-vibrators, triggered simultaneously at different locations and separating the data into files for each different vibrator.

Orthogonality of Two Sweeps

Given two sweeps $S_a(t)$ and $S_b(t)$, if the following conditions are satisfied, the two sweeps are orthogonal:

$$S_a(t)\otimes S_a(t) = A(t), \quad \text{(A(t) is not equal to zero)}, \tag{1}$$
$$S_b(t)\otimes S_b(t) = B(t), \quad \text{(B(t) is not equal to zero), and} \tag{2}$$
$$S_a(t)\otimes S_b(t) = 0, \quad (\text{or } S_b(t)\otimes S_a(t) = 0), \tag{3}$$

where $\otimes$ denotes a correlation operation. In the frequency domain, Eqs. 1 - 3 can be written as

$$S_a(f)S_a^*(f) = A(f), \tag*{(1)'}$$
$$S_b(f)S_b^*(f) = B(f), \text{ and} \tag*{(2)'}$$
$$S_a(f)S_b^*(f) = 0, \ (\text{or } S_b(f)S_a^*(f) = 0), \tag*{(3)'}$$

where the asterisk denotes the complex conjugation.

Design of Orthogonal Sweeps

A combisweep consists of two or more sequential conventional sweeps either with time gaps between them (the signal amplitude goes to zero), or without such gaps. The conventional sweeps that constitute a combisweep are called sweep-segments, and the gaps zero-segment. For combisweep A (Figure 1) based on the convolution model assumption, the correlated record $R_A(f)$ can be written as

$$R_A(f) = A(f)R^*(f) = A_1(f)R_1^*(f) + A_2(f)R_2^*(f) = A_1(f)A_1^*(f)E_a^*(f) + A_2(f)A_2^*(f)E_a^*(f), \tag{4}$$

where R(f) is uncorrelated seismic data and $E_a(f)$ is the seismic wavelet convolved with the earth's impulse response for source A, and $R_1(f)$ and $R_2(f)$ are the unique halves the uncorrelated record (Figure 1).

When two combisweeps A and B are used (Figure 2), the uncorrelated record can be written as

$$R(f) = A(f)E_a(f) + B(f)E_b(f) = A_1(f)E_a(f)+A_2(f)E_a(f)+B_1(f)E_b(f)+B_2(f)E_b(f) = \\ A_1(f)E_a(f)+B_1(f)E_b(f) + A_2(f)E_a(f)+B_2(f)E_b(f) = R_1(f) + R_2(f), \quad (5)$$

Where

$$R_1(f) = A_1(f)E_a(f)+B_1(f)E_b(f),$$
$$R_2(f) = A_2(f)E_a(f)+B_2(f)E_b(f),$$

$E_a(f)$ and $E_b(f)$ are the seismic wavelet convolved with the earth's impulse response for sources A and B, respectively.

The correlated record between combisweeps A and R can be written as

$$R_A(f) = A(f)R^*(f) = A_1(f)R_1^*(f) + A_2(f)R_2^*(f) = \\ A_1(f)A_1^*(f)E_a^*(f)+A_1(f)B_1^*(f)E_b^*(f)+A_2(f)A_2^*(f)E_a^*(f)+A_2(f)B_2^*(f)E_b^*(f). \quad (6)$$

In order to separate signals generated by sweep A from record R, we only need to design sweeps A and B in such way that (see Eq. 4)

$$A_1(f)B_1^*(f) = 0, \text{ and} \quad (7)$$
$$A_2(f)B_2^*(f) = 0. \quad (8)$$

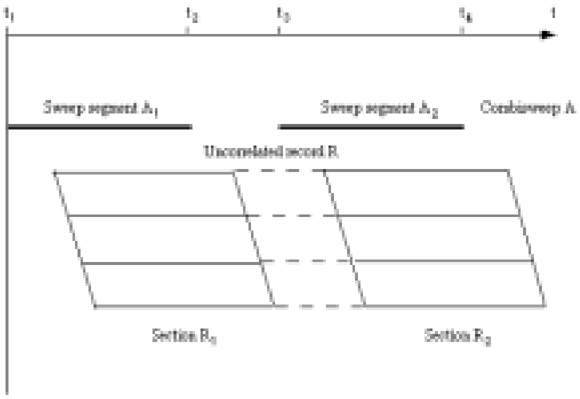

Fig. 1. A combisweep with two segments and a zero segment.

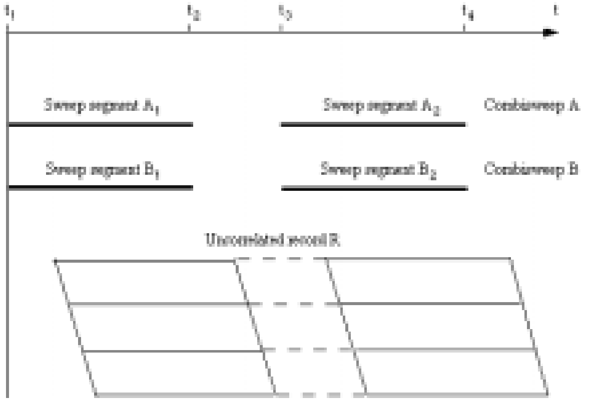

Fig. 2. Two combisweeps.

The orthogonality indicated by Eqs. 7 and 8 is more easily achieved than that shown in Eq. 3. What Eqs. 7 and 8 require is the orthogonality between *sweep segments*, not between *sweeps*. We suggest that linear up- and down- sweeps are used to design an orthogonal sweep. An example would be two orthogonal sweeps range from 15 Hz to 180 Hz with length 10 seconds (s) and listen time 2s (Figure 3). The sweep segments are A_1, A_2, and a 2s zero-segment between them for sweep A. The sweep segments B_1, B_2, and a 2s zero-segment between them are for sweep B. From time 0s to time 4s, frequencies of sweep segment A_1 change from 15 to 97.5 Hz, sweep segment B_1 from 97.5 to 180 Hz, and both segments are followed by a 2s zero segment. Then from 6s to 10s, frequencies of sweep A_2 change from 97.5 to 180 Hz and sweep B_2 from 15 to 97.5 Hz. Because there is no frequency overlap between sweep segments A_1 and B_1, Eq. 7 is satisfied. Because there is no frequency overlap between segment A_2 and B_2, Eq. 8 is satisfied as well. Therefore, sweeps A and B are orthogonal. Separation of record $R_A(f)$ and $R_B(f)$ can be easily achieved using a simple correlation operation

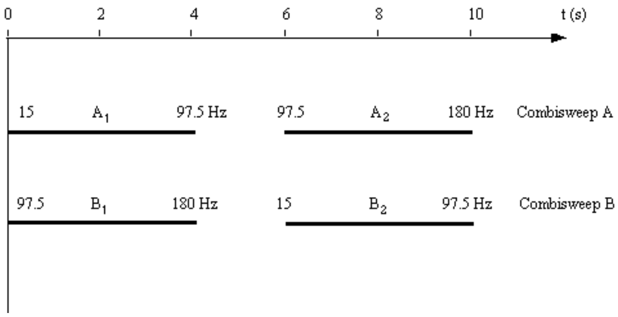

Fig. 3. An example of orthogonal sweeps.

$$R_A(f) = A(f)R^*(f), \text{ and} \tag{9}$$
$$R_B(f) = B(f)R^*(f). \tag{10}$$

or a deconvolution operation

$$R_A(f) = R(f)/A(f), \text{ and} \tag{11}$$
$$R_B(f) = R(f)/B(f). \tag{12}$$

In summary, a simple way to construct a sweep A and a sweep B to be conditionally orthogonal (Figure 3) is to start by thinking of a linear vibrator sweep. A linear vibrator sweep begins at one frequency, ends on another frequency. Frequencies of the vibrator sweep change linearly with time. The first half of the linear sweep will be the first part of sweep A. The second part of the linear sweep will be the first part of sweep B. Because the frequency content of the first part of the sweeps does not overlap, their cross-correlation is zero and thus the simultaneous sweeps are separable. For the second part of the two sweeps, the above situation is simply reversed: The second part of sweep A is the second part of the linear sweep and the second part of sweep B is the first half of the linear sweep. It should be noted that sweep linearity is not required for this method to work. Non-linear sweeps will work just as well. A linear sweep was used an example for simplicity and because it is the most common method of sweep design.

A Simulated Field Test

In 1999, a two-vibrator field test was simulated utilizing the only available vibrator at the Kansas Geological Survey. We simulated a two-vibrator case by vertically stacking two uncorrelated field records with the vibrator at two different locations 100 m apart (related to traces 128 and 148). Collecting data in this way allowed the comparison of the two-vibrator separation to the single vibrator case, giving us an estimate of the separation noise. Orthogonal sweeps A and B are 10s long with 2s listen time (Figure 3). Sweep A consists of two segments, the first one lasting 4s from 15 to 97.5 Hz and the second one lasting 4s from 97.5 to 180 Hz linked by a 2s zero segment. For sweep B, the above situation is simply reversed. Figure 4 shows the correlated data that a shot at trace 128 with sweep A was vertically stacked with a shot at trace 148 with sweep B. The uncorrelated vertical stacked data was correlated with sweep A to obtain Figure 5a that is compared to Figure 5b. Data in Figure 5b was acquired with only single vibrator at a location related to trace 128. The uncorrelated vertical stacked data was then correlated with sweep B to obtain Figure 6a that is compared to Figure 6b, which was acquired with only single vibrator at a location related to trace 148.

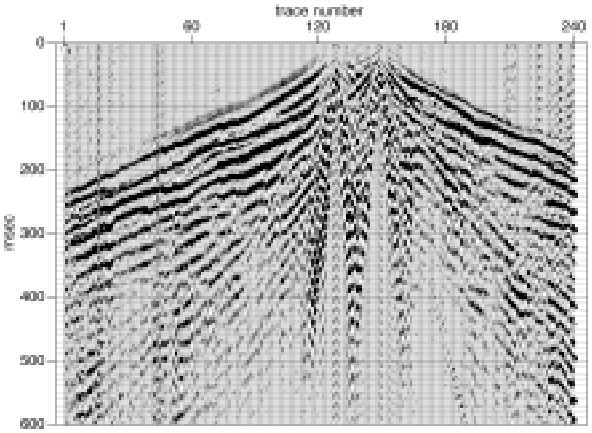

Fig. 4. Field data with a simulated two-vibrator case. One at a location is related to trace 128 and the other trace 148.

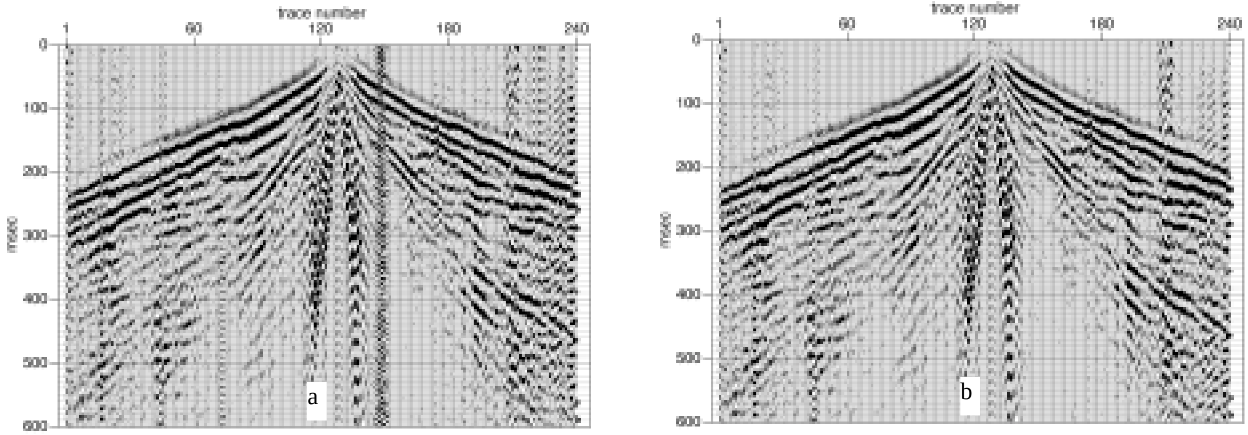

Fig. 5. Orthogonal combisweep simulated separation at station 128 (a) compared to single vibrator correlation at station 128(b).

Comparing Figure 7a with Figure 7b demonstrates the utility of this approach. A processing flow of whole trace normalization, a bandpass filter (Butterworth filter: 15-30-80-120 Hz), and the normal moveout correction was applied to ten separated data files resulting in a common midpoint (CMP) stacked section (Figure 7a). The same processing flow was applied to data acquired with a single vibrator, resulting in a CMP stacked section shown in Figure 7b.

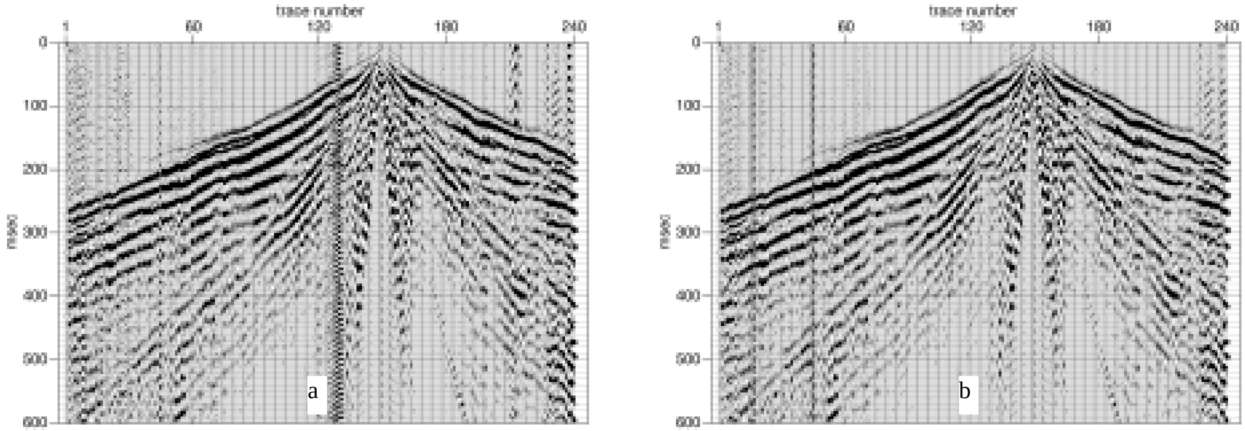

Fig. 6. Orthogonal combisweep simulated separation at station 148 (a) compared to single vibrator correlation at station 148(b).

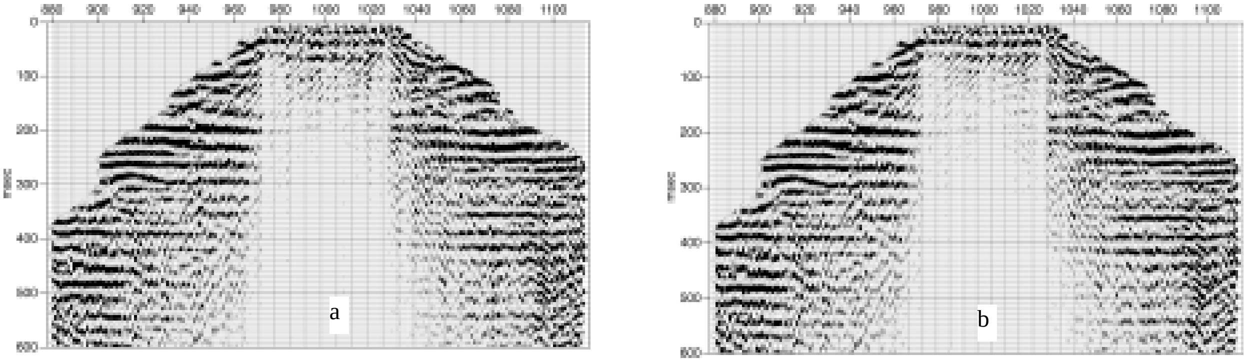

Fig. 7. A CMP stacked section from separated data (a) compared to a CMP stacked section from data acquired with a single vibrator (b). CMP numbers are on the top of figures.

Conclusions

Orthogonal sweeps designed using the concept of combisweeps allowed data separation using a simple correlation/deconvolution. Our preliminary test showed that 33 dB separation can be achieved and more than 40% acquisition time could be saved for a two-vibrator case. Orthogonal sweeps can be applied to acquisition of data when several vibrators at several locations were triggered simultaneously. Harmonics in and out of the sweep bandwidth were not that noticeable.

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