Pseudo-random coded simultaneous vibroseisms
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Summary
Phase modulated digital pilot vibrator signals using pseudo-random codes provide correlations with minimal side lobes. This property can be used to separate the contributions of vibrators emitting simultaneously.

Introduction
Simultaneous recording is coming back as a center of interest for acquisition teams, for productivity (Rozmond, 1996) or quality improvement (Baeten et al, 2000) or for multi-source monitoring (Meunier et al, 2001). Methods involving phase encoded sweeps are limited, due to harmonics and correlation side lobes. Such problems could be overcome using the ability to submit digital signals offered by new vibrator electronics.

Pseudo-random code and phase modulation

Back in 1979, A. Cunningham mentioned the possibility to replace swept-frequency sines by coded phase modulated sines. He suggested to keep or to inverse the phase of a sine at each period, according to a pseudo-random “maximum length” binary code.

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code and phase-modulated sequence

Elementary signal sequences were thus generated. The correlation of a cyclic signal, made of the repetition of some elementary sequences, by one elementary sequence gives a series of peaks, at an interval equal to the duration of a sequence. Between the peaks, side lobe amplitudes are minimal. The ratio between the peak and the side lobes is equal to the number of terms of the elementary sequence. Side lobe amplitudes may be totally cancelled if positive and negative code elements are appropriately weighted. These properties remain as long as the cyclic signal and the correlation sequence are entirely facing each other.

3-sequence cycle  single sequence  correlation

The correlation can be limited to times where the correlating sequence faces non-zero elements of the cyclic series: we obtain a peak when identical sequences are in front of each other and minimal side lobes zeros else where. The cyclic signal can be shortened if we are concerned by only a part of the minimum side lobe plateau.

For vibroseismic applications, when the sequence duration is longer than the listening time, we can thus emit a portion of a cyclic signal, made of several identical coded sequences, containing one sequence, surrounded by two intervals at least equal to the listening time.

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listening time  sequence  listening time
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If this portion of the cyclic signal is emitted, receivers will record this signal, shifted in time and with different amplitudes, for each reflection. Correlating these records with the elementary sequence over the “listening time” will generate a peak for the first event at the beginning and a minimum side lobe plateau during all the listening time and a peak for each following reflection, surrounded by flat plateaus up to the last event at the end of the listening time.
Coded simultaneous vibroseismics

As the side lobes are small or null, the different events have little interference between each other. The correlation process being symmetrical, it is also possible to emit a single sequence and correlate the records by a portion of a cyclic series containing a central sequence and two lateral listening times. This solution represents less field effort. The first one presents the advantage of correlating the powerful first events, using the central, stabilized, part of the emission, when electronic and hydraulic transitory effects have vanished and the soil under the plate is already compacted.

Distortion

The code is designed to cancel the amplitudes in the correlation outside the central lobe. The peak-to-side lobe ratio is very sensitive to the similarity of each “period” of the sequences. For a modulated sine, the transition between two periods shows cusps when the sign of the code elements changes while the transition between non-sign-changing elements remains smooth. Distortion will have different effects on both types of transitions, thus lowering the efficiency of the correlation.

This problem can be overcome by replacing the sine by a periodic curve, where both amplitude values and time derivatives are null at the edges of each period. Function Sin(1-Cos), where the period is the product of a sine period by a Hanning's window, has such properties. We are thus using the association, common in the telecommunication domain, between a carrier frequency centering the spectrum and a “formant” which determines its shape.

Transitions between changing and not-changing elements are no more asymmetrical and distortion will affect every period the same way. Harmonics will no more be an issue. As a counterpart, less energy is emitted per time interval: filtering a sine by a Hanning’s window leads to a loss of one quarter of the energy emitted during a given time.

Separation of shifted sequences records

A correlated signal without side lobes, due to correlation or to harmonics provides no interference between different events if the sequence is longer than the listening time. If the sequence is longer than twice or n times the listening time, these properties will also allow separation of simultaneous emissions.

Suppose n vibrators emitting portions of a cyclic series of maximum length sequences, each portion being shifted by an interval at least equal to the listening time with respect to the others. Reflections on a given reflector will be recorded as a sum of weighted and shifted copies, R1…Rn of the pilot signals S1, …, Sn. Correlation of one of the contributors to the record, Ri, by the correlating sequence CSj corresponding to pilot j will give a peak within the listening time if and only if i = j. If i and j are different, the correlation will only give a minimum amplitude plateau during this time interval. The record can thus be separated into its n components by successive correlation with the n respective correlating sequences.

Measurements

An experiment was performed at a test site. The source was a piezoelectric vibrator, fixed on a cement base at the surface. The receiving pattern was made up of 24 vertical geophones cemented in a well below the source, at a 5 meter-interval, between 60 and 175 m.

Three different pseudo-random code modulated signals were emitted:

1. a coded 2047 terms-sequence of a 100 Hz sine,
2. a coded 2047 term-or-24.5 s-sequence of a 83 Hz sin(1-cos),
3. a 83 Hz weighted sin(1-cos), with an emission made of a 24.5 s-coded sequence, surrounded by two 1.2 s-wings.
Coded simultaneous vibroseisms

The correlation of a record by its sequence cannot be visually differentiated from the correlation by the same sequence of the sum of two records generated with sequences shifted by an interval greater or equal to the listening time (fig. 1). The amplitude of the difference between the correlation of the sum and the correlation of one of the two records is about a hundred times below the amplitude of the greatest correlation peaks (fig. 2).

![fig 1: Correlation](image1)

![fig 2: Difference x 37 dB](image2)

A measure of the separability of two simultaneous emissions can be designed. Two shifted signals are run and recorded separately. The separability is then defined by the ratio of the maximum amplitude of the difference between the correlation of the sum of the two records, Rc1+Rc2, by the correlating sequence of one of them, CS1, to the maximum amplitude of the correlation of this record by the same correlation sequence:

\[
    Sep = \frac{A_{\text{max}}((Rc_1 + Rc_2)\times CS 1 - Rc_1\times CS 1)}{A_{\text{max}}(Rc_1\times CS 1)} = \frac{A_{\text{max}}(Rc_2\times CS 1)}{A_{\text{max}}(Rc_1\times CS 1)}
\]

The separability of shifted sequences was measured for the three signals and for each geophone.

<table>
<thead>
<tr>
<th>Separability</th>
<th>Sine 100 Hz shifted sequences</th>
<th>Sin(1-cos) 83 Hz shifted sequences</th>
<th>Winged and weighted Sin(1-cos) 83 Hz shifted sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum</td>
<td>18.9 dB</td>
<td>34.4 dB</td>
<td>36.0 dB</td>
</tr>
<tr>
<td>maximum</td>
<td>39.2 dB</td>
<td>39.4 dB</td>
<td>40.4 dB</td>
</tr>
<tr>
<td>median value</td>
<td>36.4 dB</td>
<td>38.1 dB</td>
<td>38.1 dB</td>
</tr>
</tbody>
</table>

Field measurements are, obviously, below the theoretical performances. Thirty-eight decibels are reached for shifted sequences, for a 66 dB or even infinite theoretical separability. Similar field measurements of signal separability had been reported for other methods by BP, with a maximum of 32 dB (Martin, 1993). A separability of 40 dB was since claimed with the HFVS method (Wilkinson, 1998).

Processed data

VSP processing was applied to single records and to records separated by correlation from the sum of two sets of records obtained with shifted sequences, i.e.:

- separation of up and down-going waves by FK filtering,
- deconvolution by the down-going field,
- flattening of the up-going events.
Coded simultaneous vibroseismics

Figures 3 (single records) and 4 (separated records) show no significant difference in quality.

Conclusions

Phase modulation of a periodic signal by maximum length codes provide correlations with minimal side lobes. This property makes separation of simultaneous vibrations possible with an interference measured below -36 dB. This performance is about twice the performance obtained with phase encoded sweeps. Further work and tests are needed. If these early results were confirmed, this technique might be of interest in increasing acquisition productivity and quality.

References

Cunningham, A.B., 1979, Some alternate vibrator signals, Geophysics, 44, 1901-1921
Martin, J.E., 1993, Simultaneous Vibroseis Recording, Geophysical Prospecting, 41, 943-967

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