Harmonic noise reduction opens the way for array size reduction in vibroseis™ operations
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Summary

To compensate for the reduced number of vibrators per shot point required by reductions in group interval and array size, either the recording time per surface unit must be increased or high order simultaneous recording techniques such as the slip sweep technique should be used. Yet these techniques suffer from distortion, which contaminates the data in proportion to the productivity increase generated. A method to significantly reduce this contamination is presented.

Introduction

Whereas most marine 3D surveys provide images using a 12.5-m interval, the vast majority of land 3D surveys still provide images using a 25-m interval or even more. Reducing the group interval and, in turn, the size of the source and the receiver arrays appears to be a necessary trend in land 3D seismic recording. This reduction will affect signal-to-noise ratio. Organized noise can be dealt with by well-established combinations of field and numerical filtering techniques. This noise will not be considered in this presentation. Non-organized noise is a more difficult problem to tackle. If the total area covered by the receivers is kept constant, the same amount of non-organized noise will be recorded. For instance, a 50-m source and receiver interval 3D design offers the same performance as a 25-m design with the same geophone density, four times less geophones per station and four times as many channels. This requires little extra work but significant extra equipment. However, if noise does not change, signal must also be kept unchanged. The difficulty lies in the fact that, because of their size, the number of vibrators has to be reduced in order to fit in a smaller array. To make up for a reduction of m to n vibrators, vibration time must be increased by a factor (m/n)^2. Such an increase will result in a major time and cost increase unless high order simultaneous acquisition techniques are used. The main problem with most of these techniques is their sensitivity to harmonic distortion. This presentation describes an experiment, which evaluates the damage caused by distortion and proposes a way to reduce this damage.

A six-fleet slip sweep experiment

Several techniques are available. The slip-sweep technique has the advantage of simplicity (1). It is also the technique that seems to offer the highest potential for a productivity increase. In the course of comparative tests conducted in April 2001 in Argentina (4), a 3D test survey was recorded in the slip sweep mode with the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of receiver lines</td>
<td>8</td>
</tr>
<tr>
<td>Station interval</td>
<td>25m</td>
</tr>
<tr>
<td>Line interval</td>
<td>350m</td>
</tr>
<tr>
<td>Sweep</td>
<td>[8-90] 32s.</td>
</tr>
<tr>
<td>Number of vibrator groups</td>
<td>6 groups</td>
</tr>
<tr>
<td>Number of vibrators per group</td>
<td>1</td>
</tr>
<tr>
<td>Slip time</td>
<td>6s</td>
</tr>
<tr>
<td>Acquisition mode</td>
<td>Slanted Cross array</td>
</tr>
<tr>
<td>Nominal stacking fold</td>
<td>50</td>
</tr>
</tbody>
</table>

Because of the very large ratio between the sweep length (32 s.) and the slip time (6 s.), correlation noise is spread over the four previous shot points of the mother record as can be seen in figure 1.

![Figure 1: Correlated mother record (detail). Harmonic noise contamination is stronger than reflections.](image)
Some properties of harmonic noise.

Harmonic distortion in the Vibroseis™ signal can be modeled as follows:

\[ S = F_1(t_b, f_e, t) + \sum c_i * H_i(f_b, f_e, t) \]  (1)

where

- \( S \) is the actual (distorted) signal,
- \( F_1 \) the fundamental (wanted signal),
- \( f_b \) and \( f_e \) the start and end frequency of the sweep
- \( H_i \) the harmonics,
- and \( c_i \) the proportion of each individual harmonic.

The sweep properties are such as

\[ H_i(t_b, f_e, t) = F_i(t_b, f_e, t) \]  (2)

In the \([f, t]\) plane, correlation by either the fundamental \( F_1 \) or by an harmonic \( H_i \) can be seen as focusing the corresponding energy along the frequency axis (figure 2). In this plane, for a sweep with increasing frequencies (up sweep), energy corresponding to harmonic components other than the component used for correlation is found at positive or negative times depending on whether it corresponds to a lower or higher harmonic order. For instance, after correlation by the fundamental, all harmonic noise is found at negative times (if there is no sub-harmonic). But after correlation by the 2\textsuperscript{nd} harmonic, fundamental energy is found at positive times while 3\textsuperscript{rd} harmonic energy is found at negative times (figure 2). Contaminated times can be computed from the sweep parameters. In particular, for a linear sweep, the lowest contaminated times (\(t_{1,2}, t_{3,2}\) and \(t_{1,2}\) in figure 2) are proportional to the sweep length. Amplitude of the contamination (relative to the peak amplitude of the correlation) depends upon the proportion of each harmonic component (coefficient \( c_i \) in equation 1) and on the sweep parameters. It can be shown that it is inversely proportional to the square root of the sweep length. As a result, harmonic separation will be easier on long sweeps.

Harmonic noise reduction.

Various methods have been proposed to reduce harmonic noise (3). The present method uses the decomposition of the

\[ F \]

\[ V \]

\[ R \]

\[ C \]

\[ T \]

\[ S \]

\[ M \]

\[ E \]

\[ L \]

\[ F \]

\[ V \]

\[ R \]

\[ C \]

\[ T \]

\[ S \]

\[ M \]

\[ E \]

\[ L \]

\[ F \]

\[ V \]

\[ R \]

\[ C \]

\[ T \]

\[ S \]

\[ M \]

\[ E \]

\[ L \]
data into its fundamental and harmonic components.

In the present example, harmonics of order higher than three could be neglected. The first step is to correlate the data separately by the fundamental F1 and by harmonics H2 and H3 (figure 4).

\[ D^*H_i = R^*[c_1^*F_1 + c_2^*H_2 + c_3^*H_3]^*H_i \]  

(3)

The results are then muted around the first arrival and the cross-correlations with \( i \neq j \) are neglected:

\[ \text{mute}(D^*H_i) = R^*c_1^*H_j \cdot H_i \]  

(4)

It is then possible to reconstruct the harmonic component of the data and filter it out. The input into this calculation can be a signal estimate such as the weighted sum of reaction mass and base plate accelerations as in the HFVS method \(^{(2)}\); or it can be the seismic data themselves. In the present case, superior results were obtained using seismic data. In a slip sweep mother-record, the last shot-point is not affected by harmonic noise. It is processed first, so that the previous shot-point becomes free of harmonic noise. This shot-point can then be processed and so on until the first-shot point. Figure 3 shows the mother record of figure 1 after application of this procedure. Reduction in harmonic noise is estimated between 15 and 25 dB. Figure 5 shows a detail of this record. Note that no fundamental data can be seen in the difference between the processed and un-processed data. After stack, the slip sweep data is virtually identical to conventional (no slip sweep) data even though, on figure 6, the fold available for the comparison is only four.

**Conclusion**

In this example, a significant reduction in harmonic noise was achieved. Consider a seismic crew operating in flip flop mode with two sets of three vibrators. It can (ideally) record 112 VPs of one single 32-s. sweep at 50-m intervals in one hour. The same crew, operating in slip sweep mode (6 seconds slip time) with the same six vibrators in six single-vibrator sets can (ideally again) record 600 VPs (almost six times more) per hour at 25-m intervals. This advantage can be used to totally eliminate whatever is left of harmonic noise while providing a vastly superior spatial sampling to achieve enhanced organized noise filtering and more accurate imaging.

**References**


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Harmonic noise reduction

Figure 5: Correlated Shot point. Left: raw. Center: after harmonic noise reduction. Right: estimated harmonic noise

Figure 6: 4-fold CDP stack. Left: raw. Center: after harmonic noise reduction. Right: Conventional (no slip sweep) single-vibrator acquisition