Establishing the limits of vibrator performance - experiments with pseudorandom sweeps

Timothy Dean*, WesternGeco

Summary

Many methods have been developed over the last 50 years to generate pseudorandom sweeps for vibroseis sweeps, some of which have never before been tested. I give an overview of the different generation methods and their relative advantages and disadvantages. Tests showed that vibrators can struggle to emit some of these sweeps, particularly if they contain segments of the same polarity, sudden changes in instantaneous frequency, or small amplitude/high-frequency fluctuations. Although use of pseudorandom sweeps was initially promoted to improve the shape of the autocorrelation wavelet the most promising use is to reduce interference in simultaneous surveys.

Introduction

The vibroseis technique involves transmitting energy into the earth over an extended period, typically more than 10 s, via a baseplate that is held down against the surface of the ground by the weight of the vehicle. The signal, which controls the oscillatory baseplate motion, is referred to as a sweep and typically consists of a series of oscillations whose instantaneous frequency monotonically changes over the sweep duration. This variation in sweep frequency is usually linear. Although a variety of non-linear sweeps have been suggested, their use has been limited.

Another form of vibroseis drive signal is a pseudorandom sweep, still referred to as a sweep despite the fact that it is not monotonic. The use of pseudorandom sweeps was first suggested by Wischmeyer (1966) as a method to improve the shape of the autocorrelation wavelet. Other suggested benefits include reducing the potential for infrastructure damage and increasing low-frequency content. Pseudorandom sweep usage has been limited because vibrator controllers were ill-suited to their non-monotonic wave forms (Burger and Baliguet, 1992). The introduction of more advanced controllers and a surge of interest in high-productivity vibroseis methods have led to renewed interest in the utilisation of orthogonal pseudorandom sweeps for simultaneous surveys. In what follows, I describe the characteristics of the predominant design techniques and their relative advantages and disadvantages. I include some results from recent tests conducted to determine the ability of a vibrator to emit such sweeps.

Tests

The tests were conducted using a DX80 Desert Explorer vibrator and a VibPro controller. The outputs from the baseplate and reaction-mass accelerometers were combined to calculate the ground-force estimate (Sallas, 1984) which was used to determine the ability of the vibrator to transmit each sweep. For the results shown in this paper the ground-force and pilot traces were scaled so that they have the same mean peak values.

Generation techniques

I divide pseudorandom sweep generation methodologies into five main categories: binary sequence convolution, binary sequence filtering, pulse sweeps, sweep rearrangement, and non-binary random numbers; I shall describe each of these in turn.

Binary sequence convolution methods are those that involve the convolution of a binary sequence, typically a maximal-length sequence, with another waveform. See Sarwate and Pursley (1980) for a detailed review of pseudorandom sequences. Wischmeyer (1966) combined a binary sequence with two waveforms with constant frequency (the ‘carrier’ frequency), one having positive amplitudes and one negative, to generate the signal. Sweeps can be generated using either a full-cycle or half-cycle waveform. The half-cycle version is superior to the full-cycle version in both wavelet shape and in bandwidth, but the energy is lower (a full-cycle sweep has the same energy as a linear sweep, while the half-cycle sweep has 25% less). The autocorrelation sidelobes for Wischmeyer sweeps are minimal around $t = 0$ when compared to an 8 to 80-Hz linear sweep but for larger lag values (> ~1 s) the autocorrelation values are actually larger. The power spectrum of Wischmeyer sweeps (Figure 1) shows a large notch at twice the carrier frequency, and a variety of smaller notches below. There is significant low-frequency content, but a considerable decrease in power with increasing frequency.

Although not mentioned by other authors, if multiple Wischmeyer sweeps are generated using Kasami or Gold sequences (Sarvate and Pursley, 1980) then they have low crosscorrelations, for example the average crosstalk between $-5$ and $+5$ s (a typical record length) for two sweeps is 37 dB down with the maximum being 25 dB down.

The experimental results show that the vibrator is incapable of successfully emitting the half-cycle sweeps as it cannot transmit successive pulses of the same polarity (see the red box in Figure 2a). Full-cycle sweeps do not have such sequences and thus were transmitted more successfully (Figure 2b).
Establishing the limits of vibrator performance

Figure 1: Autocorrelation wavelets (left) and power spectra (right) of half-cycle (black) and full-cycle (grey) Wischmeyer sweeps generated using a carrier frequency of 40 Hz.

Figure 2: Pilot (blue) and ground-force (green) traces for (a) half-cycle and (b) full-cycle Wischmeyer sweeps.

Binary sequence filtering methods involve, as the name suggests, taking a binary sequence and then filtering it to the desired bandwidth (Figure 3). Burger and Baliguet (1992) recognised that the sidelobes on such sweeps would be significant, but expected that these would decrease with stacking if different sweeps were used. They also recognised that sweep energy was lower than that of a linear sweep at the same drive level, in their case by 6 dB (~50%), although this varies depending on the bandwidth (the narrower the bandwidth, the greater the difference).

Sallas et al. (2011) detail a method developed for generating sweeps for simultaneous surveys. The method begins by generating a series of Gold sequences. These sequences are then filtered to the desired spectral shape in the frequency domain. The sweeps are then modified (a total of 10 to 20 iterations is stated as being typical) to minimise their crosscorrelation in the window of interest. The resulting sweeps have separation values between the autocorrelation peak and the peak crosscorrelation in the minimisation window (defined as the time lags of interest) of about 45 dB (Sallas et al., 2011). After generating the sweeps, a process of waveform shaping is applied to boost the energy of the sweep, resulting in the sweep energy being 2-3 dB less than that of a linear sweep.

Iranpour et al. (2009) use simulated annealing to generate individual sweeps with optimum autocorrelation wavelets or sets of sweeps with optimum crosscorrelation characteristics in a time window of interest. The cost function, which determines the success of the current stage of the sweep(s), includes a) the autocorrelation of the sweep, b) the deviation in the power spectra/spectrum, for this example between 10 and 100 Hz, and c) the standard deviation of the crosscorrelation between the sweeps, if multiple sweeps are being generated. The sweeps are perturbed a large number of times until the optimum solution is achieved. After the sweeps are generated, they can be shaped to the appropriate spectrum with begin and end tapers applied in the time domain. The effect of the process is to reduce interference significantly within the minimisation window. Figure 4 shows the autocorrelation and crosscorrelation for a pair of Iranpour sweeps, the separation in the minimisation window (~4 to +4 s) averages less than ~50 dB, with a maximum of ~40 dB. As the autocorrelation is included in the cost function, this too has an optimum shape, superior to a linear sweep that covers the same bandwidth. Similarly, the variation in the power spectrum is much lower than a sweep generated from purely random numbers. As for other pseudorandom sweeps, the energy is less than 50% of linear sweep with the same length.

The vibrator was successful at emitting the sweeps (Figure 5, see also Nasreddin, Dean, & Iranpour, 2012).
Establishing the limits of vibrator performance

Pulse sweeps are somewhat of a misnomer, as they consist of a series of pulses separated by pseudorandom time delays. Taner’s (1972) preferred implementation consists of a series of square wave pulses (although other pulses such as spikes were considered acceptable) with a duration of between 4 and 8 ms.

Sweep rearrangement methods, as described by Goupillaud (1976), are based on randomly rearranging the segments of an existing sweep. Goupillaud’s method consists of dividing a linear sweep into segments, each containing only amplitudes of positive or negative values. These segments are then randomly reordered, but keeping consecutive negative and positive segments, to generate the pseudorandom sweep. The randomness of the sweep results in significant sidelobes appearing at random intervals, rather than the rapidly decaying sidelobes of the linear sweep, and causes significant distortion in the power spectra of the sweeps.

Experimental results show that if the segments are shuffled completely randomly the vibrator struggles where the frequency of adjacent segments changes significantly (see the red box in Figure 6a). If the shuffling of the segments is limited, so that the frequency of adjacent segments is lower, then the vibrator is more successful at transmitting the sweep (Figure 6b).

Non-binary random number methods utilise random number sequences other than pseudorandom binary sequences. Muir (1984) invented a method of generating sweeps whose amplitudes have a zero mean, Gaussian distribution, and are statistically stationary (i.e. the statistical characteristics of the sweep do not change over the duration of the sweep). His process involves filtering a series of normally distributed random numbers to a restricted bandwidth. The imposition of a Gaussian distribution limits the number of samples with high amplitudes (Figure 7), and thus the energy of the sweep is just 16% of that of a linear sweep. Such sweeps must be generated at a sample rate equal to the Nyquist of the maximum frequency required in the sweep otherwise energy appears outside the bandwidth of interest and is then lost when the sweep spectrum is shaped.

Experimental results (Figure 8) show that the vibrator is effective at sweeping Muir sweeps, possibly due to the fact they are are the same as those embedded in the vibrator controller. By using a distribution of random numbers that is heavily skewed towards higher values the sweep energy was more than doubled without affecting data quality.

Castle (1988) created a method aimed at generating sweeps by pre-specifying the shape of the autocorrelation. His method involves taking a target autocorrelation wavelet and determining its amplitude spectrum. A set of uniformly distributed random numbers is generated between -1 and
Establishing the limits of vibrator performance

These random numbers are then multiplied by $2\pi$ to give a random phase spectrum. This phase spectrum is combined with the amplitude spectrum of the desired autocorrelation and an inverse Fourier transformation is applied.

Discussion

Pseudorandom sweeps can be compared on the shape of their autocorrelation (both its width and size of the sidelobes near and far from the peak value), their energy compared to a linear sweep and whether the spectrum is an input to the sweep design process or a result of it. If used for simultaneous acquisition the crosstalk must also be compared. A summary of such attributes for the different methodologies described in this work is shown in Table 1.

For non-simultaneous surveys there is no compelling reason to use these sweeps in place of linear sweeps. The energy of the sweeps for all but the half-cycle Wischmeyer sweeps is less than a linear sweep although this can be improved using methods such as that described by Sallas et al. (2011). Being unable to define the spectral shape of the sweep is a significant drawback, although one can filter the sweeps to a desired bandwidth. However, this reduces the sweep energy further.

Conclusions

Pseudorandom sweeps can be used to reduce side-lobes near the centre of the autocorrelation although not without increasing sidelobes at greater time lags.

Tests showed that vibrators struggle to emit pseudorandom sweeps that contain segments with the same polarity, sudden changes in instantaneous frequency or small amplitude/high frequency fluctuations.

The most promising use of pseudorandom sweeps is for simultaneous surveys where they can significantly reduce crosstalk.

Table 1 Summary of sweep generation attributes. ‘Sidelobes-near’ are $<$1 s and ‘sidelobes-far’ $>$1 s. Energy is relative to a linear sweep with similar bandwidth (where applicable) and equal length. The ‘spectrum shape’ column describes whether the spectrum of the sweep is an input ‘Yes’ or output ‘No’ of the sweep design process, ‘Yes*’ indicates methods where post-generation filtering is applied. If the design method can be used for simultaneous acquisition the separation in terms of the maximum crosstalk (in dB) is also given. The ‘emission’ column gives an indication of the vibrator’s ability to transmit the sweep measured as the ratio between the energy content of the pilot and ground-force, not in comparison to a linear sweep.

<table>
<thead>
<tr>
<th>Method</th>
<th>Sidelobes-near</th>
<th>Sidelobes-far</th>
<th>Width</th>
<th>Energy</th>
<th>Spectrum shape</th>
<th>Separation</th>
<th>Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary Sequence Convolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wischmeyer (1966) full-cycle</td>
<td>Red</td>
<td>Red</td>
<td>Blue</td>
<td>100</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wischmeyer (1966) half-cycle</td>
<td>Blue</td>
<td>Red</td>
<td>Blue</td>
<td>75</td>
<td>No</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Binary sequence filtering</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sallas et al. (2011)</td>
<td>Green</td>
<td>Red</td>
<td>Red</td>
<td>70</td>
<td>Yes*</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Iranpour et al. (2009)</td>
<td>Blue</td>
<td>Red</td>
<td>Red</td>
<td>30</td>
<td>Yes*</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Pulse sweeps</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taner (1972)</td>
<td>Blue</td>
<td>Red</td>
<td>Red</td>
<td>15</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rearrangement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goupillaud (1976)</td>
<td>Blue</td>
<td>Red</td>
<td>Red</td>
<td>60</td>
<td>No</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Random Number Methods</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muir (1984)</td>
<td>Green</td>
<td>Red</td>
<td>Red</td>
<td>16</td>
<td>Yes*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Castle (1988)</td>
<td>Blue</td>
<td>Red</td>
<td>Red</td>
<td>14</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

© 2012 SEG  
SEG Las Vegas 2012 Annual Meeting
EDITED REFERENCES
Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2012 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Castle, R. J., 1988, Method for generating and collecting random vibratory seismic data wherein a pre-specified wavelet of minimum side lobe content is always produced in the final correlations by maintaining domain consistency: U. S. Patent 4,768,174.


Muir, F., 1984, Seismic exploration using non-impulsive vibratory sources activated by stationary, Gaussian codes, and processing that results in distortion-free final records particularly useful in stratigraphic trap determination: U. S. Patent 4,486,866.


