Vibroseis – a Counter-Intuitive Tool

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Overview

Geophysics and intuition are often poor partners. Most of us have had the experience of expecting a certain outcome from an experiment, only to be surprised by a totally opposite result. I have been fortunate to have been involved in many hundreds of vibroseis test programs in my career, and I strongly suspect that no other geophysical tool has been so misunderstood. The vibroseis method involves using a piece of machinery to generate a controlled force at the source point (usually a relatively long-duration, variable-frequency cosine signal). The first problem in understanding vibroseis parameters is to recognize that this machine is not perfect and may not perform exactly as we might expect. Therefore, our parameter selection must recognize the behaviour of the machine coupled with the behaviour of the earth in response to the generated signal.

Many simplifying assumptions regarding vibroseis sweep theory have propogated through the years. The result is that many geophysicists now accept these concepts as true fundamental precepts. For successful vibroseis sweep design, it is important to embrace some broader geophysical concepts and divorce ourselves from narrow simplifications. In this paper, I will focus on a few such examples.

Vertical Stacking

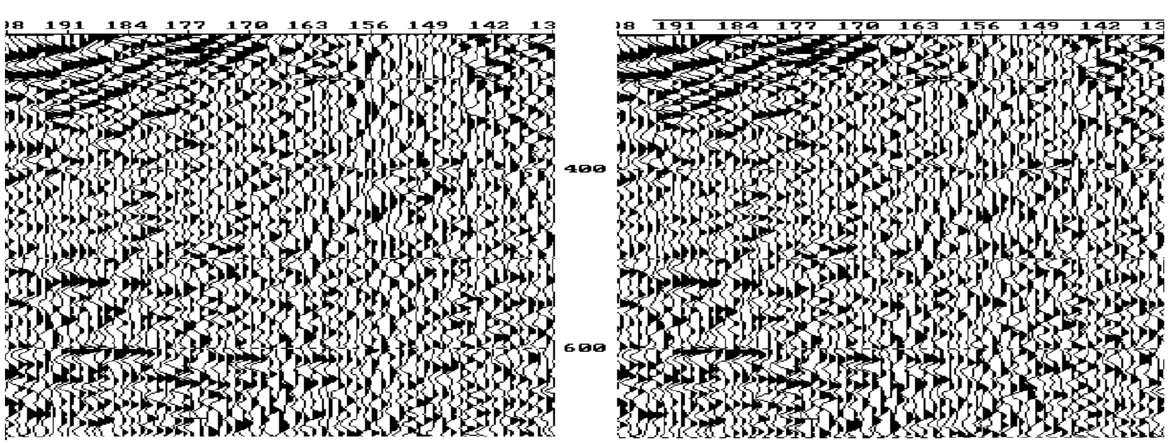
It is common practice to record several sweeps at each source point and sum these separate records together to form one data set for that source point. The intent is to take advantage of the principle of superposition, whereby multiple observations that contain similar signal and dissimilar noise, when summed together will result in a constructive summation of signal and destructive interaction of noise. For fully correlatable signal and gaussian distributed random noise, such a summation will result in an improvement in signal to noise ratio (on the summed trace relative to any individual contributing trace) equal to the square root of the number of summed traces. This leads to the common perception that noisy seismic data can be improved by increasing the number of sweeps per vibrator source point (VP).

This concept requires more investigation. We must first recognize different types of noise. Here, I will choose to describe noise in four categories. *Time variant* noise occurs when the character of noise changes unpredictably from one moment to the next. Wind is often a good example of time variant noise. The way grass or sand or leaves blow around a reciever location during one record is not likely to be the same as the character such noise will exhibit on subsequent records.

Reciever variant noise is noise that may be unique to each receiver group. For example, a pump jack operating close to one receiver group will cause a type of noise on that group that will not be recorded by other receivers elsewhere along the seismic line. Similarly, *source variant* noise is unique to certain source locations. For example, a patch of muskeg in one area may significantly alter our source signature compared to hard pastures at other source points.

It is important to note that these groupings of noise are for a convenience of description only. They are not rigorous. For example, receivers laid out over a mountain ridge are generally very susceptible to windy conditions. So does this represent time variant noise or receiver location noise? The answer is "a bit of both". In practice, this is very common, some of our receiver and/or source locations may experience higher levels of random (time variant) noise than others.

However, it is my experience that the vast majority of what we refer to as "noisy data areas" represent a fourth category of noise. *Offset variant* noise (sometimes refered to as "source-generated" noise) is quite variable from area to area. In general, this category of noise encompasses various surface (or near-surface) wave phenomena such as ground roll, air blast, trapped mode, and scattered surface waves that may appear like "random" noise due to their poorly sampled representation. This last type (scattered surface waves) is particularly misleading as it can easily be confused with time-variant random noise. The best way to recognize time-variant versus source-generated noise is to record two records from one source point at two different times. Display the two records and flicker back and forth between them. Time-variant noise will "sparkle"; peaks or troughs of noise will appear at different times and places on the two records. Source-generated noise will be repeatable on the two records.



The two records in the previous figure were recorded about 10 minutes apart from the same source point, using identical sweeps. The record on the left represents a single sweep while the record on the right is the sum of 12 sweeps.

When we vertically stack individual sweeps contributing to a vibroseis record, we hope to cancel noise by the principle of superposition. Successive vibrator sweeps within one source point will be recorded at slightly different times but will originate from just one source point, will use the same set of receivers and will generate the same offset-variant (source generated) noise. Therefore, superposition will only act to suppress the time variant noise.

On the other hand, CDP stacking mixes together traces of different offsets, source locations and receiver locations that were recorded at different times. Therefore, CDP stacking effectively attenuates all of the noise types identified above. CDP fold is far more valuable than vertical stack fold in vibroseis. Consider a 2-D seismic program using 20 meter receiver intervals where we would like to introduce some 1000 seconds of sweep time ever kilometer. This could be accomplished by creating 10 VP's per kilometer (100 m source interval) and producing 10 sweeps of 10 seconds per VP. Assuming useable offsets of 0 to 2000 meters, this would result in a 20 fold CDP line where each source record was the vertical stack of 10 sweeps. Alternatively, we could record 2 sweeps of 10 seconds at a source interval of 20 meters (equal to our receiver interval – 50 VP's per km). We now have a CDP fold of 100 using individual records created by summing just 2 sweeps. The latter strategy will generally produce far superior data provided that the sum of 2 sweeps makes a record sufficiently strong for the processor to conduct velocity and statics analyses.

In both the above scenarios, 1000 seconds of sweep energy is injected for each kilometer of data. Both scenarios will create the same signal strength and will require the same effort and time to record (therefore the costs will be the same). The latter alternative (high CDP effort, low vertical stack) will do a better job of sampling all types of noise. The first stategy (high vertical stack, lower CDP effort) will be ineffective if the noise is not time variant. Furthermore, vertical stacking is usually accomplished in the field (individual sweeps are not generally preserved on tape). Therefore, any static or dynamic differences from one sweep to the next will be averaged in the summation. By recording smaller sums more frequently, we allow the processor an opportunity to stabilize amplitude, phase and timing differences that often occur between successive sweeps.

Therefore, higher vibroseis effort should be accomplished by generating more records at frequent source intervals rather than using more sweeps at sparse source intervals. Vibroseis represents a wonderful opportunity to achieve full stack array recording in an affordable manner.

Sweep Length and Sweep Rate

Another commonly stated "fact" is that signal to noise ratios can be improved by increasing sweep length. Again, the improvement is proportional to the square root of the increase. This statement assumes that sweeps are linear and of invariant bandwidth. The more correct statement is that signal to noise ratio is inversely proportional to sweep rate. Sweep rate is simple the rate of change of frequency divided by the rate of change of time. For non-linear sweeps, this is measured instantaneously and varies as the sweep progresses. This dependence of signal to noise ratio on sweep rate is an important factor to remember when considering non-linear sweeps.

Sweep rate is also a very important factor in the behaviour of the vibrator machine and its ability to deliver a closer approximation to our desired reference sweep.

Drive Level

Unfortunately, we are still hearing of geophysicists requesting machines to operate near their maximum theoretical potential (i.e. their hold down weight). This attitude is often reflected by the statement "I requested these big vibs so that I can generate big signal – now crank that drive level up to 95%". Unfortunately, the vibrators are very imperfect machine. When asked to drive at levels near or beyond their hold down weight, they tend to turn into giant pogo-sticks. An 80,000 lb machine jumping up and down on the ground is NOT what we want.

In fact, driving the actuator with a force anywhere near equal to the hold down weight will result in excessive harmonic distortion. This distortion is not correlateable with our desired, controlled sweep; and therefore it appears as another type of organized noise in our data. The useful signal we generate with a sweep is related to our drive level times the distortion-free portion of our ground force (i.e. 1 – THD). Typically, a machine driven at 90% drive level will generate in the order of 30% harmonic distortion. Therefore, the net signal remaining is 70% of the 90% drive, or 63% of the hold down weight of the vibrator. The remaining components are 27% noise due to harmonic distortion and 10% excess hold down weight controlling the behaviour of the vibrator.

Now consider dropping the drive level to 70%. Many geophysicists worry that they will lose signal or will have to increase the number of sweeps to overcome this reduction (this perception is wrong in many ways!). In fact, the lower drive level will result in 30% of the hold down weight exceeding the drive level (and therefore controlling the mechanical behaviour). It is normal to see a reduction in harmonic distortion to about 10%. Now our net signal input will be 90% of the 70% drive, or 63% of the hold down weight of the vibrator. Note that this is the same net fundamental force as in the previous example. However, the noise due to harmonic distortion will now be reduced to 7%.

Therefore, we must recognize that large vibrators are not created only to give us large signals, but rather to create enough potential excess hold down weight to allow the machine to behave in a more controlled, linear manner.

Non-Linear Sweeps

Most geophysicists have learned about earth absorption (attenuation) and know that high frequencies are attenuated in shorter time intervals than lower frequencies. This results in a log-linear (dB per Hz) shaping of the recorded amplitude spectrum. To compensate for this cruelness of Mother Nature, many like to use hi-dwell non-linear sweeps. For many reasons, these hi-dwell sweeps do not work as well as we might expect. Sweep tapers (necessary for controlling Gibbs effect) begin to act as surprisingly severe low-cut filters. Rapid sweep rates in the low frequencies create noisy data with poor penetration. The vibrators' phase locking circuits fight throughout the rapid sweep rates early in the sweep. The concept of compensating for absorption requires that we study the absorption curve at the primary target depth. At other depths the compensation will be incorrect.

In general, we have found that hi-dwell sweeps are generally in-effective and are often destructive to most prospects except those that concentrate only on very shallow data. Surprisingly, we have recently been implementing many lo-dwell non-linear sweeps. The philosophy behind this relates partly to the need to generate stronger low-frequencies in order to "carry" the high frequencies deeper into the earth. This theory is based on a recognition of the static coefficient of friction (a term not currently included in the wave equation usually used to describe elastic propagation of sound energy).

In fact, the lo-dwell sweep makes great sense for multi-zone targets. Deeper targets generally return lower frequency data. We waste time if we try to sweep much beyond what Mother Nature is prepared to return to our sensors. Therefore, deep targets usually demand longer sweeps limited in their upper frequencies. However, such a limited sweep will offer no opportunity to recover higher frequencies that may be available from some of our shallower objectives. Such shallow reflectors will return some high frequencies without using long sweeps to inject this energy. Therefore, in multi-zone prospects, we want sweeps that spend a long time in the lower frequencies, but allow a short period of sweep energy in higher frequencies. The lo-dwell sweep accomplishes this very well. It also has the side-benefit of being quite easy on the machinery.

Summary

Vibroseis has evolved significantly over the years. Along with technical developments, our understanding of the behaviour of the machinery and its interaction with physical ground surfaces has expanded. We are moving further from naïve, simple models for vibroseis sweep design. We now recognize many of the interactions and trade-offs involved in parameter selection. Optimizing vibroseis data requires an in-depth understanding of the behaviour of the tools, as well as a recognition of the value of better spatial sampling in the source domain. Do not expect one set of guidelines to always dictate the use of vibroseis. Rather, recognize the tool as a versatile, flexible energy source that can be customized to provide optimal data in a broad variety of situations.