Attenuation of Vibrator Harmonic Ghosts

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Summary

Vibrator sweep signals, transmitted into the subsurface, contain harmonic components due to nonlinearities in the vibrator system and due to the ground's non-linear response to the vibratory force. The harmonic energy produces a distortion in the correlated records and appears as a noise train displaced from each primary reflection. The noise trails the primary when the pilot sweep begins at a high frequency and ends at a low frequency (downsweep). For upsweeps, the noise appears as a forerunner. This paper evaluates the characteristics of harmonic ghosts in terms of time of arrival, strength and frequency content. Adverse affects of the distortion, on adjacent reflections, are shown to be minimized by: (1) increasing the sweep length, (2) reducing the sweep bandwidth, (3) utilizing an upsweep, (4) stacking alternate polarity sweeps, (5) stacking variable phase sweeps and (6) stacking variable frequency sweeps. Advantages and disadvantages of each attenuation method are evaluated.

Introduction

The vibrator technique imparts a frequency modulated sinusoidal signal (sweep) at the surface of the earth. The propagating wave arrives at the geophone with a time delay corresponding to the distance the wave has travelled. The geophone records the superposition of the long wave trains reflected from all acoustic impedance boundaries. A crosscorrelation of the input sweep signal with the geophone response effectively collapses the long sweep signal to a simple wavelet. The motion of the base plate may contain harmonic distortion due to nonlinearities in the servo-mechanical vibrator system. Such distortion is usually minimized by detecting the base plate motion and feeding back an error signal to the electrical drive control. Flexing of the base-plate may also introduce distortion due to insufficient rigidity.

The ground's non-linear reaction to the force exerted by the vibrator also causes a significant level of distortion. Second harmonic distortion of the order of 30 to 100 percent of the fundamental was observed by Seriff (1977) with the degree of distortion varying as a function of the near surface characteristics. Harmonics present in the radiated sweep produce a distortion tail in the autocorrelagram, in the case of a downsweep, causing interference with later arriving and weaker reflections. The correlation of a pilot sweep with a distorted sweep produces two components. The first being the autocorrelation of the fundamental and the second being the crosscorrelation of the fundamental with its harmonic. Harmonics of upsweeps produce forerunner noise trains which are less of a problem since they interfere with earlier, stronger reflections.

The harmonic ghost is caused by the presence of repeating frequencies in the radiated signal. The fundamental will crosscorrelate with its harmonic at a displaced time as shown in Fig. 1. The distortion time interval can be determined by finding the time of coincidence of duplicate frequencies in the fundamental and harmonic signals. The harmonic ghost begins at time T_1 which is the time required to bring the highest frequency in the harmonic in alignment with the same frequency in the fundamental. The harmonic ghost is dispersed over a long time duration with the ending time occurring at T_2 where the highest frequency in the fundamental aligns with the same frequency in the harmonic.

T_1 and T_2 are related to the harmonic order, the sweep length and the lowest and highest frequencies in the fundamental. When the pilot sweep changes linearly the ghost time can be calculated by:

$$T_1 = (k-1)\, Tf_1/W \qquad T_2 = (k-1)Tf_2/kW$$

Where: T = sweep length in seconds
f_1 = lowest sweep frequency in Hertz
f_2 = highest sweep frequency in Hertz
W = sweep bandwidth in Hertz ($f_2 - f_1$)
k = harmonic order

Trailing ghosts are particularly detrimental to the correlated field data since the noise interferes with later — weaker reflections. An upsweep places the harmonic ghost at an earlier time with the noise interfering with higher amplitude reflections. The downsweep, however, is commonly used on field crews because vibrator control at low frequencies is easier with downsweeps than with upsweeps. Synchronization of base plate motion with the sweep signal depends on servo feedback. A full cycle of wave motion is fed back in a shorter time duration when the sweep begins with a high frequency (downsweep).

Seriff derived a method for computing the amplitude of the harmonic ghost based on its frequency spectrum. He showed the amplitude to be directly proportional to the primary amplitude and the level of harmonic distortion in the radiated sweep and inversely related to the square root of the sweep length and the sweep bandwidth. Therefore, the ghost amplitude can be reduced by increasing sweep length and/or sweep bandwidth. However, sweep frequencies are usually selected on the basis of surface noises and absorption characteristics of the geologic section. There is little benefit in generating high frequency energy at the surface if during

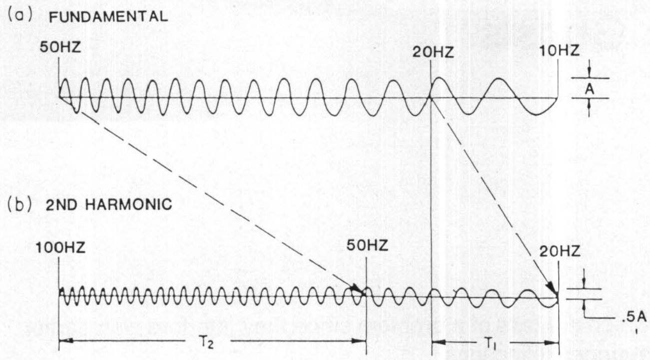

FIGURE 1
Frequency duplication in harmonic distortion.

propagation it is attenuated to a level significantly below the ambient background noise.

Methods of attenuating the harmonic ghost

Harmonic distortion can be minimized by utilizing a low distortion pilot sweep signal and a well designed electro-mechanical vibrator system. The error signal, detected as the difference in base plate accelerometer output and the pilot sweep signal, is used to adjust the electrical drive signal to obtain good synchronization. Distortion due to base plate flexing may be reduced by decreasing the area of the base plate or by increasing its mass. However, the base plate area is usually selected for good ground coupling and a small base plate mass, relative to the reaction mass, is desirable for good system performance.

Harmonic distortion due to the ground's non-linear reaction to the force exerted by the vibrator, may be the most significant problem. Ground distortion varies as a function of vibrator drive level and ground conditions. Second harmonic distortion of up to 100 percent of the fundamental may be present. Higher order harmonics are less significant due to the filtering effect in correlating the pilot sweep with the geophone response. For downsweeps, the refraction first arrival generates a significant problem due to its high amplitude relative to the subsequent reflections. The size of the first arrival can be reduced by the use of geophone patterns, source patterns and offset spreads.

Other methods of attenuating the harmonic ghost include:

1. Increasing the sweep length and decreasing bandwidth
2. Employing upsweeps
3. Stacking alternate polarity sweeps
4. Stacking variable phase sweeps
5. Stacking variable frequency sweeps

Sweep length and bandwidth affect the start time and duration of the harmonic ghost. The equations for T_1 and T_2 show that the ghost can be delayed by increasing the length of the sweep and/or by reducing the sweep bandwidth. Sufficient delay may place the ghost beyond the time of the deepest reflection of interest. However, increased sweep length means an increase in field recording time and increased correlation time. Increased sweep length will reduce the peak amplitude of the harmonic ghost and spread the noise train over a longer time interval.

The use of an upsweep would place the harmonic ghost at an earlier time overlapping stronger reflections. Factors to consider include: relative strength of reflections, length of noise train and relative times of reflections and noise. The upsweep is also undesirable from the point of rapid synchronization of base plate motion with the pilot sweep.

The stacking of alternate polarity sweeps was suggested by Sorkin (1972). His method exploits the fact that the record associated with each 'Vibrator Point' consists of a stack of several records. Sorkin's method alternates the polarity of individual sweeps with a 180 degree phase compensation applied to the received data prior to stacking. The 180 degree phase shift causes the fundamental to be additive. But, this phase shift causes the harmonic to be shifted by a full cycle resulting in subtraction of the harmonic energy. This technique eliminates even harmonics to the extent that harmonic character and amplitude are duplicated on successive records. Due to changes in surface conditions the theoretically exact cancellation is, in practice, only a reduction. The method does not eliminate odd harmonic distortion.

The stacking of variable phase sweeps was proposed by Rietsch (1981) and is applicable when four or more sweeps are recorded at each vibrator point. Rietsch's method is an extension of the alternate polarity technique with the advantage of attenuating both odd and even harmonics. Each sweep is generated with a phase shift equal to 360/n where n is the number of sweeps per vibrator point. The phase shift is not a simple time displacement since each frequency present in the sweep must be shifted by 90 degrees. Each record is individually phase compensated and summed. Schrodt (1987) evaluated the variable phase method in West Texas. Selection of the variable phase sweep technique over the alternate polarity method would only be justified on the basis of significant 3rd harmonic distortion when broad bandwidths are utilized.

Stacking variable frequency sweeps attenuates harmonic ghosts in a manner similar to the variable phase technique. The procedure can be used when 2 or more sweeps are recorded at each vibrator point. The frequency spectrum of each sweep is varied, resulting in changing characteristics of the harmonic ghost. Individual records must be cross-correlated independently before stacking.

Figure 2 illustrates the variable frequency technique with model data. Attenuation of the harmonic ghost is obtained by summing 8 variable frequency sweeps. Figure 3 shows a correlated field record containing significant harmonic ghosting related to the refraction first arrival. A variable frequency sum at the same location (Fig. 4) is effective in attenuating the ghost. When the harmonic noise varies randomly between sweeps, the attenuation will equal the square root of the number of sums. Due to the cyclic nature of the noise, the actual attenuation will be somewhat less. The selection of starting and ending frequencies are critical since this shapes the frequency spectrum of the final sum. A selection could be made to give a boxcar spectrum, but better

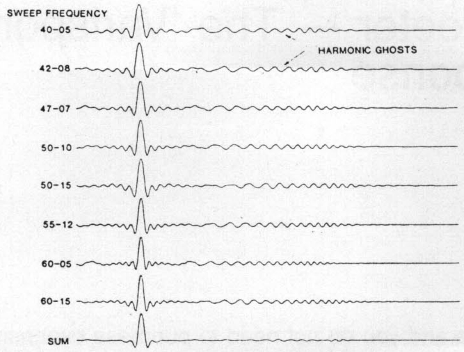

FIGURE 2
Harmonic attenuation by variable frequency sweep.

SWEEP = 80-12 HZ, 4 SECONDS

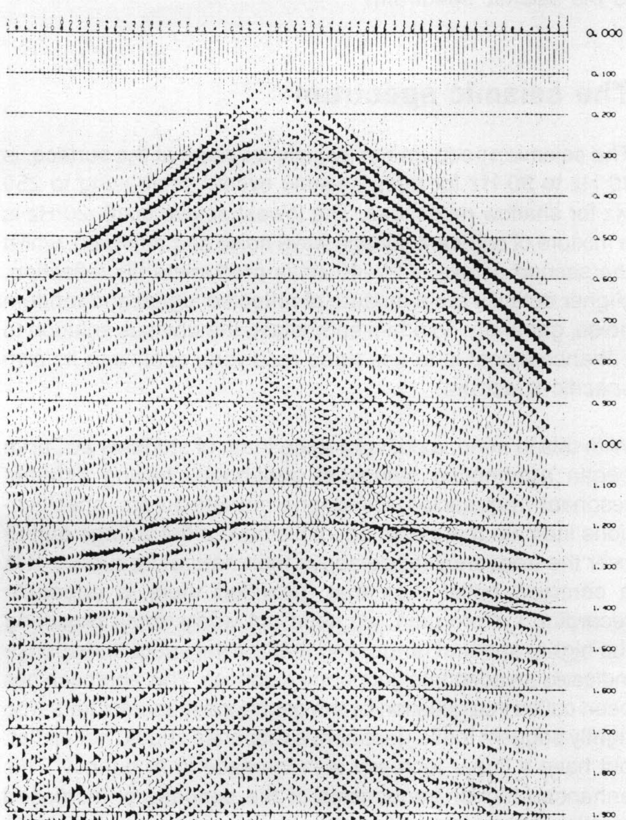

FIGURE 3
Correlated field record

wavelet characteristics are obtained with a tapered spectrum. This method also has the advantage of reducing side tail oscillations adjacent to the main lobe of the autocorrelation wavelet.

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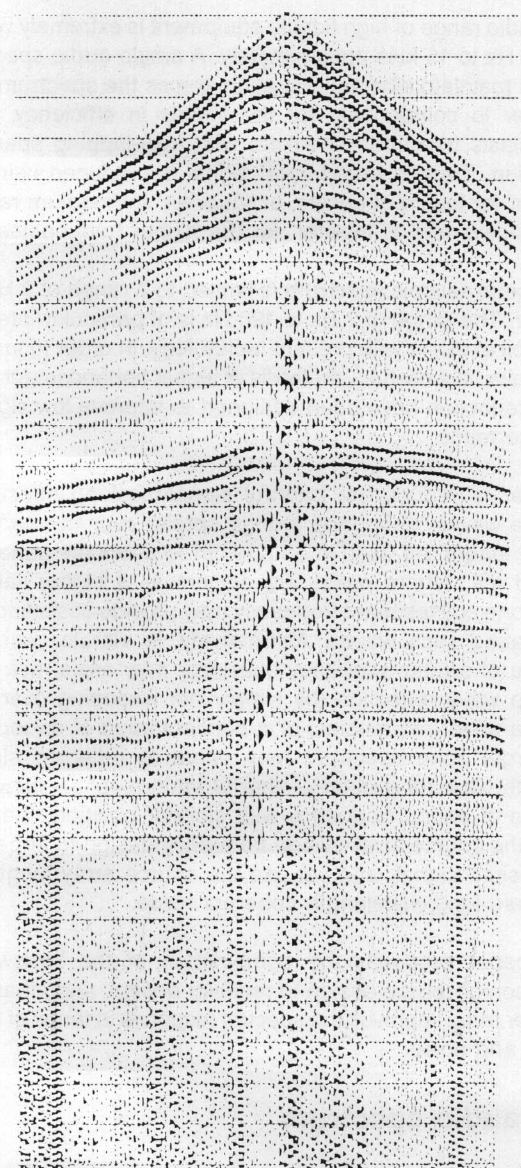

FIGURE 4
Correlated/stacked field record.

LENGTH = 8 SEC.
VARIABLE SWEEP:
70-10 72-14
74-18 76-22
78-26 80-36
82-34 82-36