Low-frequency vibroseis data with maximum displacement sweeps

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Several recent advances in land-seismic acquisition equipment and processing algorithms have encouraged exploration geophysicists to reconsider the potential benefits of energetic low frequencies for geophysical applications, imaging beneath high-velocity and highly absorbing formations, deep imaging, acoustic impedance inversion, velocity model estimation in geophysically complex areas, and inversion of surface waves to characterize near-surface elastic properties.

On the receiver side, the growing use of accelerometers in surface and borehole seismic surveys has enabled acquisition with high signal-to-noise ratio of frequencies lower than 2 Hz. Hydraulic vibrators, which are the most widely used onshore seismic sources, have their output energy limited at low frequencies by mechanical constraints, such as the maximum reaction mass displacement. Only low-actuator forces can be used to drive the vibrators at these low frequencies which, in turn, can yield extremely long sweeps in the absence of a design criterion or if a design is used that is too conservative.

In this article, we will first briefly review the geophysical applications that would benefit from energetic low frequencies. We will then list the standard sweeps that could be used to enhance the low-frequency content and will then review a new sweep design method developed by Bagaini et al. (2005) that explicitly incorporates the mechanical and hydraulic specifications of available vibrators in the design procedure. The sweeps, which are called *maximum displacement sweeps*, permit the optimal use of modern seismic vibrators to transmit the desired ground-force power spectral density to the subsurface.

The ground force is not measured directly during most surveys, but it is typically estimated using vibrator-control data. A model of the interaction between the baseplate and the ground (Sallas, 1984) is the most popular and the one used in this article. To verify the conclusions drawn using the estimated ground force, we have acquired surface and borehole seismic data during controlled experiments. These data confirm the observations made with vibrator control data. Surface seismic data demonstrate that, for deep targets, imaging can substantially benefit from energetic low frequencies. The quantitative analysis of borehole seismic data demonstrates that the superior energy content of maximum displacement sweeps at low frequencies displayed by vibrator control data is preserved after wavefield propagation.

Geophysical applications of energetic low frequencies. The exact definition of low frequencies in seismic exploration depends on the type of acquisition (land or marine), on the source used, and on the geology of the location where the survey takes place. Herein, we define the low-frequency range as 3–10 Hz.

The quality of deep imaging and imaging beneath highly absorbing formations is improved in the presence of energetic low frequencies because they are less attenuated than high frequencies. Moreover, the attenuation of high frequencies over that of low frequencies increases inversely with the effective quality factor. Quality factors as low as 15 have been found in basalts (Maresh et al., 2006). In these situations, only low frequencies can provide an acceptable signal-to-noise ratio for the target reflections, and it is therefore worth paying attention to them.

Vertical resolution depends, among other parameters, on the frequency-dependent, signal-to-noise ratio. The width of the seismic wavelet main lobe (assumed to be converted to zero phase) is inversely proportional to the signal's average frequency. The ratio between the amplitudes of the main and secondary lobes controls the capability to discriminate events in a seismic section. This ratio is proportional to the ratio of the signal maximum and minimum frequencies. Therefore, an increase of an octave of bandwidth at low frequencies would produce the same effect on this ratio as an increase of an octave at high frequencies, which is much more difficult to achieve because of the seismic attenuation.

Seismic volumes can be inverted to obtain relative changes in acoustic impedance. The transformation from relative to absolute impedance values requires data with good signal-to-noise ratio at low frequencies, ideally down to dc. Typically, seismic velocities and well-log data are used to provide an estimate of the low frequencies where these are missing from the surface seismic data. However, uncertainties in the velocity model and sparseness of the well-log information imply that assumptions must be made, compromising the quality of the inversion results. Surface seismic data with more energetic low frequencies will reduce the information gap and may deliver the two octaves of high signal-to-noise ratio bandwidth, which is commonly used (rule of thumb) to verify if the seismic data are fit for acoustic impedance inversion.

Surface waves are always generated in land-seismic surveys and are generally regarded as noise that must be attenuated in the field with appropriate receiver arrays or in the early processing stages. The concept that the surface wave's phase velocity depends on the near-surface elastic properties (Haskell, 1953), mainly on the shear-wave velocity, has been exploited extensively in global seismology (Ewing et al., 1957) and in civil engineering (Nazarian and Stokoe, 1984) for near-surface characterization. The use of surface waves in seismic exploration has been limited because the seismic exploration industry is interested in the near-surface compressional velocities to estimate static corrections and, therefore, assumptions about the Poisson's ratio must be made to obtain them from shear-wave velocities. A second reason that surface-wave use has been limited is that the receiver arrays attenuate surface waves in the field. However, this reason would disappear with the widespread use of point-receiver acquisition systems. A third reason is that the sampling depth of the surface waves is proportional to the wavelength, and unless low frequencies are generated, the penetration depth of this method is limited. The availability of energetic low frequencies would increase the

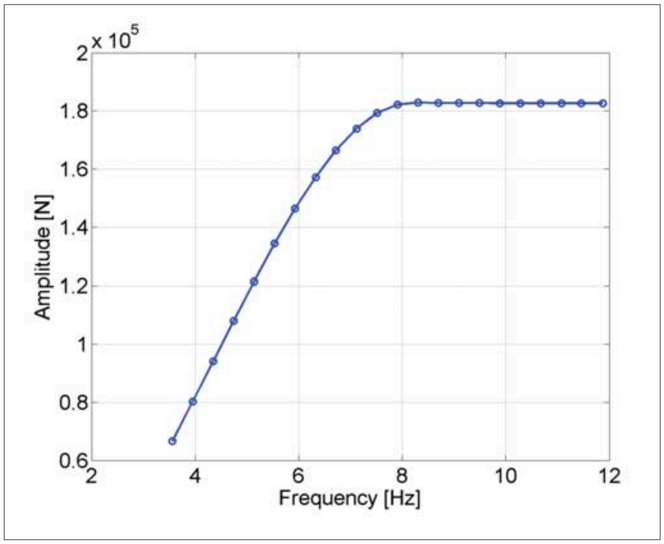

Figure 1. *Example of the frequency-dependent fundamental force that can be generated with a seismic vibrator whose peak force is 60 000 lbf (264 000 N). The maximum fundamental force, which has been set as the value at which neither the mechanical nor the hydraulic specifications of the vibrator are exceeded and the maximum total harmonic distortion is lower than 20%, is used to design maximum displacement sweeps.*

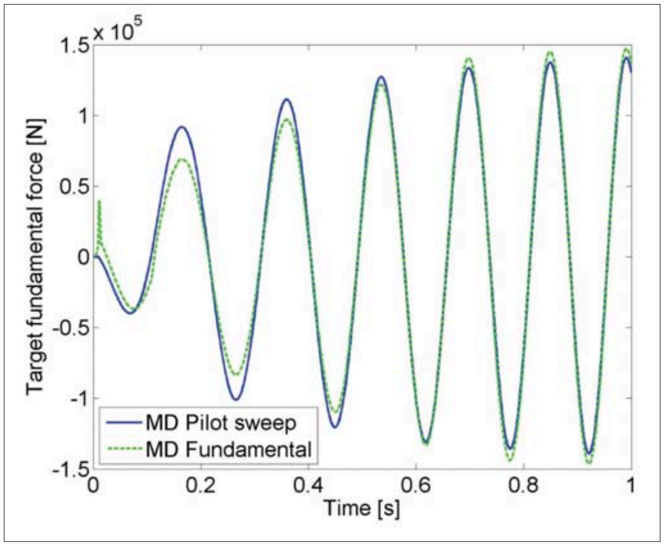

Figure 2. *Example of front end for a 10-s maximum displacement sweep. Minimum frequency (3 dB down) is 5.2 Hz; vibrator peak force is 80 000 lbf (353 000 N). The reference sweep (blue solid line) closely matches the actually delivered fundamental component of the ground force (green dashed line).*

penetration depth of these methods to values of interest in seismic exploration for determination of static corrections or even for characterization of the overburden.

Velocity analysis in geophysically complex areas is still a challenge for the seismic exploration industry. In the first steps of the velocity-model updating process, velocity-model uncertainties lead to destructive interference of the signals. The low frequencies are therefore essential to guarantee the convergence of standard processing steps such as migration velocity analysis. More recently, Sirgue and Pratt (2004) have shown that low frequencies are needed in the first steps of their waveform inversion method that operates in the frequency domain. The actual value of the minimum frequency at which a satisfactory signal-to-noise ratio must be available depends on the accuracy of the starting model and can be very low if the initial model is inaccurate.

Standard methods to enhance low frequencies in vibroseis acquisition. Nonlinear vibroseis sweeps are often designed to boost the high frequencies; however, they could also be designed to boost the low frequencies, or both. Current techniques use front- and back-end tapers that are designed according to signal processing considerations to minimize the Gibbs' phenomenon in the power-spectral density of the sweep. These tapers should guarantee that the vibrator mechanical specifications are not exceeded. However, these tapers, which are defined and applied in the time domain, do not explicitly take into account the vibrator limitations at low frequencies. The vibrator limitations are in fact defined as a frequency-dependent maximum fundamental force (Figure 1) that, using the maximum displacement sweep design reviewed in the next section, can be mapped onto a time-dependent amplitude front end.

Jeffryes and Martin (2003) developed a method called *composite sweep* that aimed at enhancing the low-frequency content of vibroseis acquisitions by combining a low-amplitude and low-frequency sweep with a standard sweep. This method requires phase matching of the two sweeps at the overlapping frequencies.

Review of maximum displacement sweeps theory. According to a widely accepted model (Sallas, 1984) of vibrator/Earth interaction, the ground force is equal to the mass-weighted sum of the reaction mass and baseplate accelerations. The dominant component of the low-frequency ground force is the reaction mass acceleration. The baseplate acceleration is negligible at low frequencies and increases up to the baseplate/soil resonance frequency, which depends on the soil elastic properties and the vibrator. This soil resonance frequency has a typical value of 30 Hz. The baseplate acceleration then levels off in the high frequencies, where the baseplate flexure is the limiting factor for the transmission of energetic seismic signals to the Earth's interior.

At low frequencies (3–8 Hz in modern seismic vibrators), if the hydraulic system is adequate and the hold-down weight prevents any decoupling phenomena, the reaction mass maximum displacement is the limiting factor for the energy that can be transmitted to the ground. Maximum displacement sweeps (Bagaini et al., 2005) have a variable sweep rate at the front end (in upsweep surveys) and a target fundamental force that permits transmission of the maximum energy to the ground given the vibrator mechanical and hydraulic constraints. The required power spectral density of the ground force, which is a key geophysical requirement that depends on the target depth, absorption of the formations, and ambient noise of the survey, can therefore be achieved with acceptable harmonic distortion. The achievable ground-force power spectral density at low frequencies depends on the vibrator specifications, geophysical requirements such as the sweep length, the acceptable harmonic noise, and, to a lesser extent, on the ground conditions.

Mathematical models of the vibrator/ground interaction such as that described in Lerwill (1981), or experimental investigations for the type of vibrator available, are used to determine the frequency-dependent maximum driving force that can be used without exceeding the vibrator specifications (Bagaini et al., 2005). Figure 1 is an example of the max-

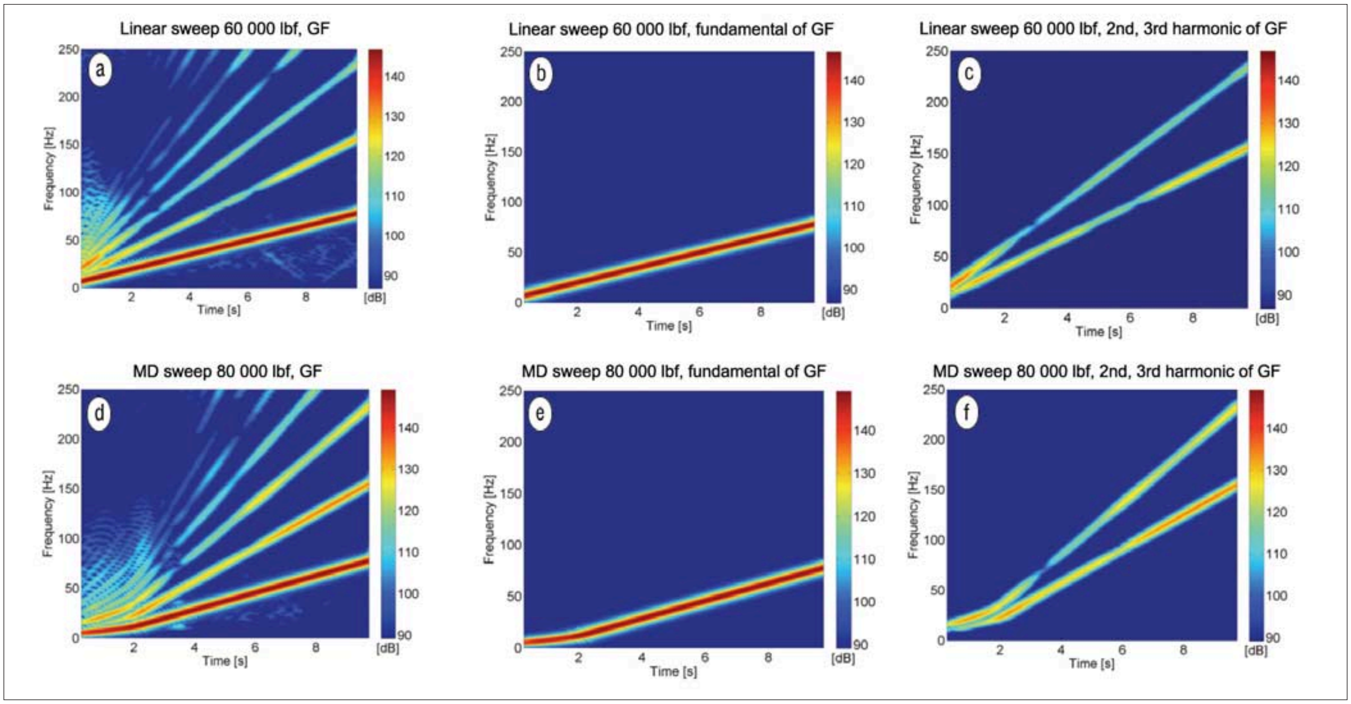

Figure 3. Comparison of the ground force generated by a 60 000-lbf vibrator shaking a linear sweep and the ground force generated by an 80 000-lbf vibrator (Desert Explorer) shaking a maximum displacement sweep. (a) Time/frequency representation, (b) extracted fundamental, and (c) extracted second and third harmonic for the linear sweep. (d), (e), and (f) are the corresponding figures for the maximum displacement sweep with the Desert Explorer.

imum force that can be used to drive a vibrator (34 000-kg hold-down weight) while generating a total harmonic distortion of less than 20%. Denoting this driving force with $DF(f)$ and the instantaneous frequency, which is a monotonic function of time, with f_i, a maximum displacement sweep can be written as the following function of time:

$$a(t) = DF\left(f_i(t)\right)\sin\left(2\pi\int_0^t f_i(\tau)d\tau + \alpha\right), \qquad (1)$$

where α is the sweep initial phase. $f_i(t)$ can be obtained by inverting the instantaneous time, whose expression was derived in Bagaini (2006) and Bagaini et al. (2005), and here reported:

$$t_i\left(f_i\right) = \int_{f_{\min}}^{f_i} 4\frac{psd(\eta)}{DF^2(\eta)}d\eta, \qquad (2)$$

where $psd(\eta)$ is the desired ground-force power spectral density and f_{min} is the sweep minimum frequency. The time derivative of $f_i(t)$, which is called *sweep rate*, is an important parameter because the sweep length is inversely proportional to it. An example of maximum displacement sweep front end is shown in Figure 2.

Ground force and harmonic noise. A field experiment was carried out using a standard vibrator with a rated peak force of 60 000 lbf (264 000 N), and the 80 000-lbf (353 000 N) WesternGeco Desert Explorer vibrator. Figure 3a shows the time/frequency representation of the ground force generated by the 60 000-lbf shaking a linear sweep (10 s, 5–80 Hz, 200-ms front- and back-end taper). Figure 3d shows the ground force generated by the Desert Explorer shaking a maximum displacement sweep of the same length. The fundamental component of the ground force—the signal that we wish to transmit to the Earth's interior—can be estimated using the method described in Jeffryes (2002). Figures 3b and e show that this estimation is quite accurate. The harmonics, particularly the second and third, which are the most critical, can be estimated with the same method (Figures 3c and f). The time/frequency representation of the maximum displacement sweeps are substantially different than the corresponding linear sweep at low frequencies because they spend more time at those frequencies and more energy is transmitted to the Earth's interior. The harmonics are kept under control throughout the seismic bandwidth. The definitions of the maximum displacement sweep and the linear sweep above 10 Hz are essentially identical. The slight differences of the harmonics at frequencies above the seismic bandwidth are most likely caused by slightly different ground conditions at the two shot locations.

Figure 4 shows the power-spectral density of the fundamental components extracted from the ground forces shown in Figures 3b and e. The Desert Explorer, shaking a maximum displacement sweep, generates a significantly more energetic fundamental force at low frequencies because of the maximum displacement front end. The peak force and hold-down weight of the 80 000-lbf vibrator produce the more energetic high frequencies transmitted to the ground. The theoretical increase in ground-force power spectral density for frequencies above the front-end taper is proportional to the square of the ratio 80 000/60 000 and inversely proportional to the sweep-rate ratios. For the two sweeps used during the field test, this theoretical increase is 2.1 dB. The results shown in Figure 4 highlight that the measured fundamental power spectral densities are in excellent agreement with the theoretical predictions. The dB scale is relative to a power spectral density of 1 N^2/Hz^2.

Surface seismic data. WesternGeco has acquired several 3D data sets using maximum displacement sweeps. The sweep lengths and the seismic bandwidth were different, but the common objective was the generation of an energetic fundamental component of the ground force at low frequen-

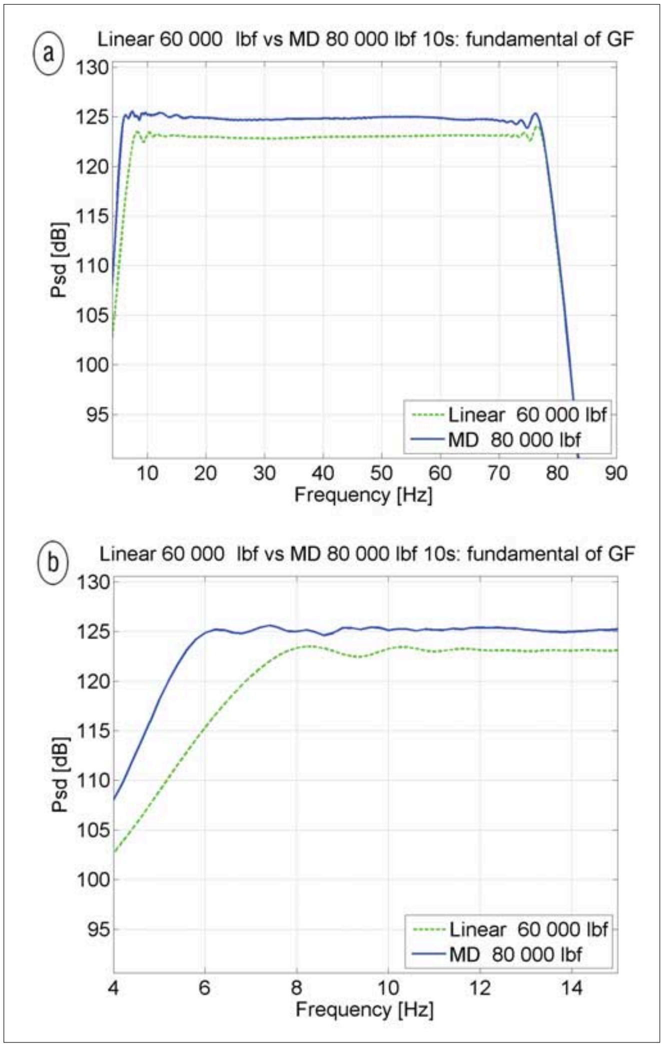

Figure 4. *Fundamental components of the ground force generated by a 60 000-lbf vibrator shaking a linear sweep and an 80 000-lbf vibrator shaking a maximum displacement sweep. The fundamental components of the two ground forces have been extracted, as shown in Figure 3, and their power spectral densities are shown in (a). A close-up of (a) at low frequencies is in (b). The vertical scale is dB with respect to 1* N^2/Hz^2.

cies while keeping the harmonic distortion under control. In most of these cases, an entire and comparable data set acquired with standard sweeps was not acquired for economical reasons and because the challenging ground-force power spectral density requirements could not be met with standard sweeps.

A 5-km long 2D line using an 80 000-lbf vibrator was acquired during a field test in the Middle East using linear and maximum displacement sweeps whose ground-force power spectral densities are shown in Figure 5a. Taking into account the target depth, the overburden absorption, and the ambient noise, it was decided to use 16-s sweeps. The linear sweep was an upsweep with minimum and maximum frequencies of 6 Hz and 80 Hz. The front- and back-end tapers were Blackman 500 ms. Figure 5a shows that the maximum displacement sweep ground force is consistently more energetic than the one measured for the linear sweep. The time/frequency representations of the ground forces in Figures 5b and 5c show similar levels of harmonic distortion for the linear and the maximum displacement sweeps.

Both data sets were processed using the same processing sequence to obtain a CMP stack. Figure 6 shows two close-up views of the deep horizons of these two stacks. The more energetic low frequencies obtained with the maximum displacement sweep penetrated deeper into the Earth's interior to enable imaging of interpretable horizons.

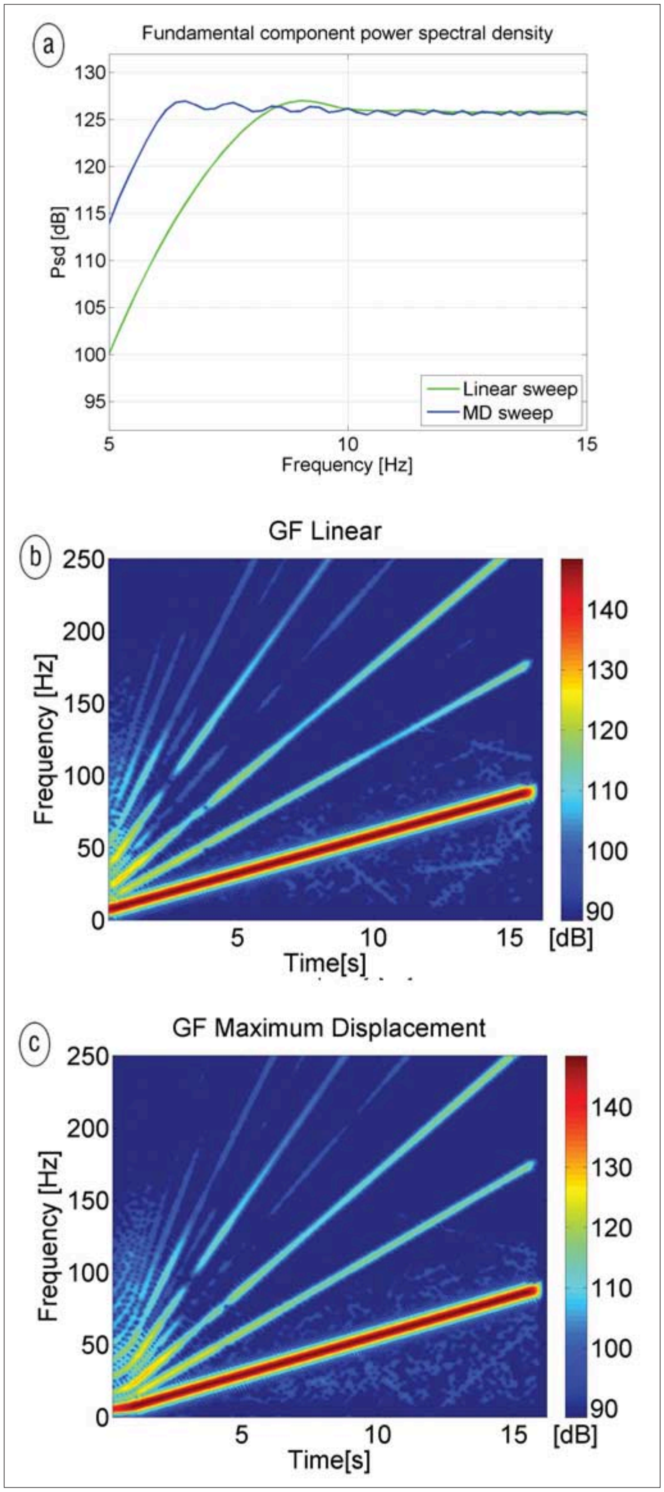

Figure 5. *Surface seismic field test. Both linear and maximum displacement sweep emitted by an 80 000-lbf vibrator. (a) Power spectral densities of the fundamental component of the ground-force measurements for the linear (green line) and the maximum displacement (blue line). (b) Time/frequency representation of the measured ground force for the linear sweep. (c) Same as (b) for the maximum displacement sweep.*

The signal-to-noise ratio for a deep target was estimated and the results are shown in Figures 7a and 7b. This analy-

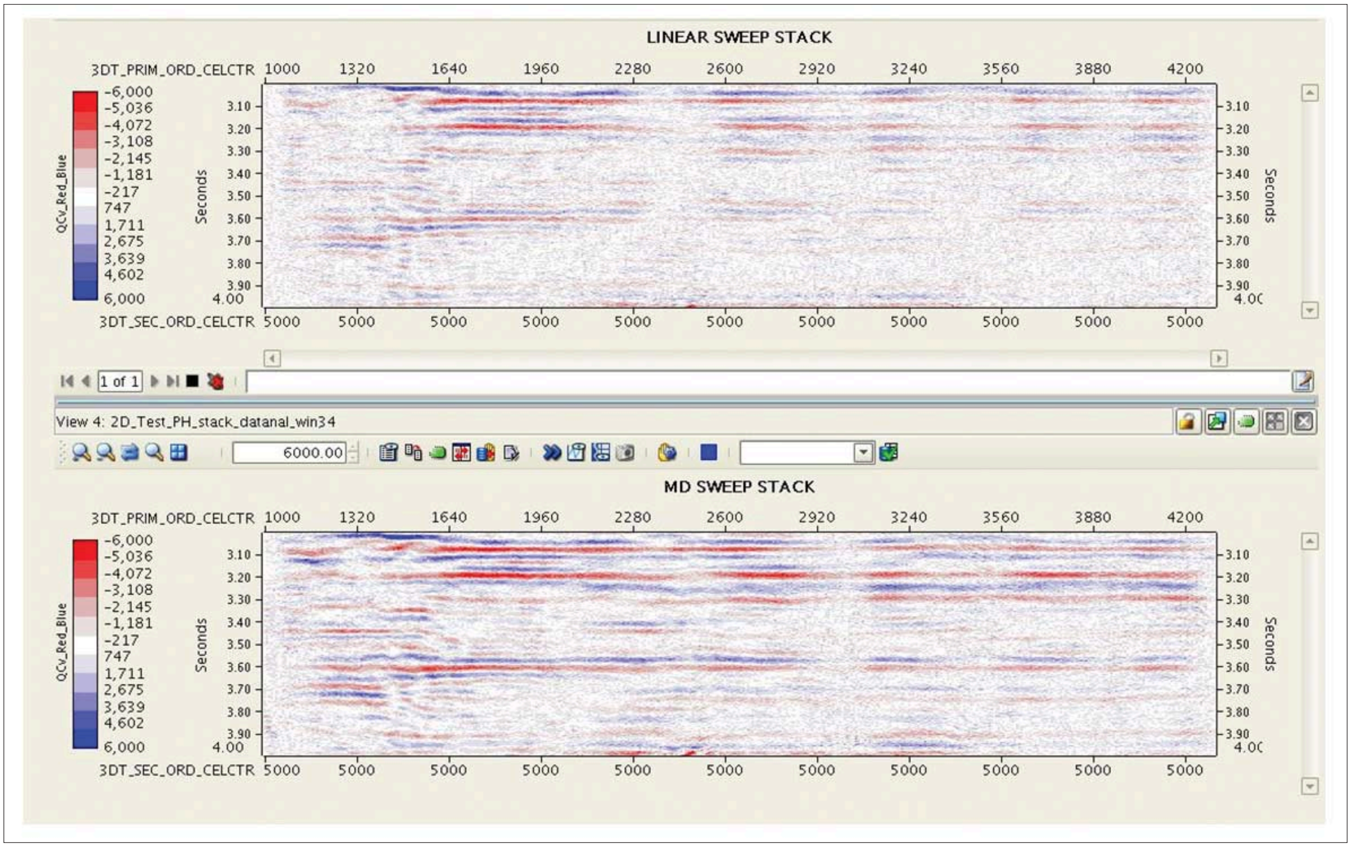

Figure 6. Surface seismic test. (top) CMP stack obtained using a linear sweep (5–80 Hz, 16 s). (bottom) CMP stack obtained using a maximum displacement sweep of the same length.

sis of poststack data confirms the observations made for the ground force; a substantial improvement of the signal-to-noise ratio at the low frequencies can be obtained with maximum displacement sweeps. The actual value of this range depends on the vibrator available and on the time that we are willing to spend on low frequencies. In the case of a state-of-the-art heavy vibrator, this range is 5–8 Hz.

Borehole seismic data. A borehole seismic experiment was conducted using a well whose maximum depth is about 800 m. Five 3-C geophone accelerometers (GACs) were installed at 15-m intervals at depths between 669 and 730 m. GACs (Obuchi and Fujinawa, 1991) are moving-coil dynamic accelerometers whose amplitude response in the acceleration domain is flat all the way down to below 2 Hz. One 80 000-lbf vibrator was used throughout the experiment to shake linear and maximum displacement sweeps from the same location. The shot location was 180 m offset from the well head. The presence of infrastructure in the vicinity of the well, and the need to drive the vibrator at high forces at the limits of its capability ruled out a smaller offset. The feedback loop was locked on the ground-force phase, which was estimated with the weighted sum of the reaction mass and baseplate acceleration. The vibrator electronic controller was the ION VibPro.

The linear sweep was a 5–80 Hz upsweep with 10-s and .25-s front- and back-end Blackman tapers. The maximum displacement sweep length was also 10 s and was designed to generate a fundamental component of the ground force more energetically than the linear sweep in the frequency range between 5 and 9 Hz. Lower start frequencies of 4 and 3 Hz were also considered, but it was observed during

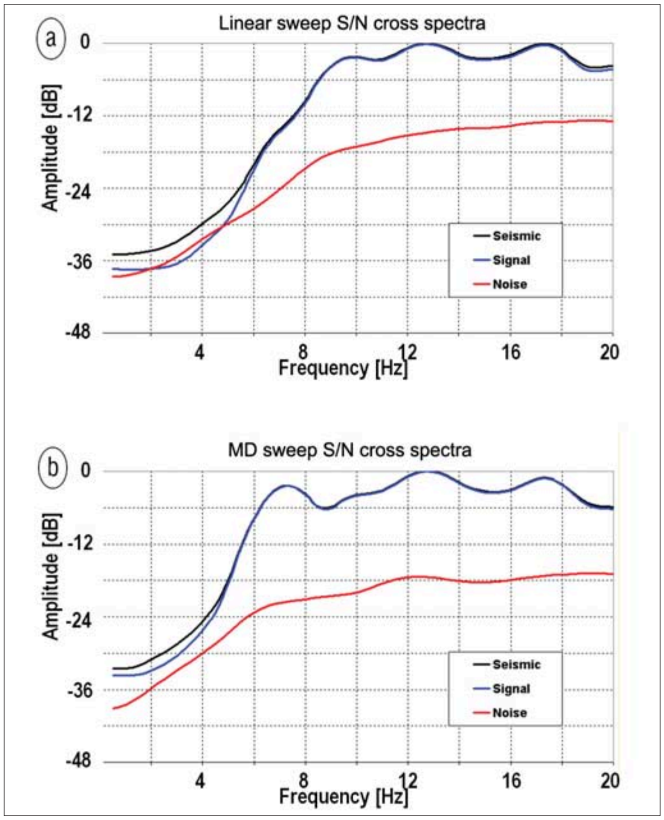

Figure 7. Surface seismic test. Signal-to-noise ratio at target depth for the CMP stacks obtained with (a) the linear sweep and (b) the maximum displacement sweep whose ground-force power spectral densities are shown in Figure 5a.

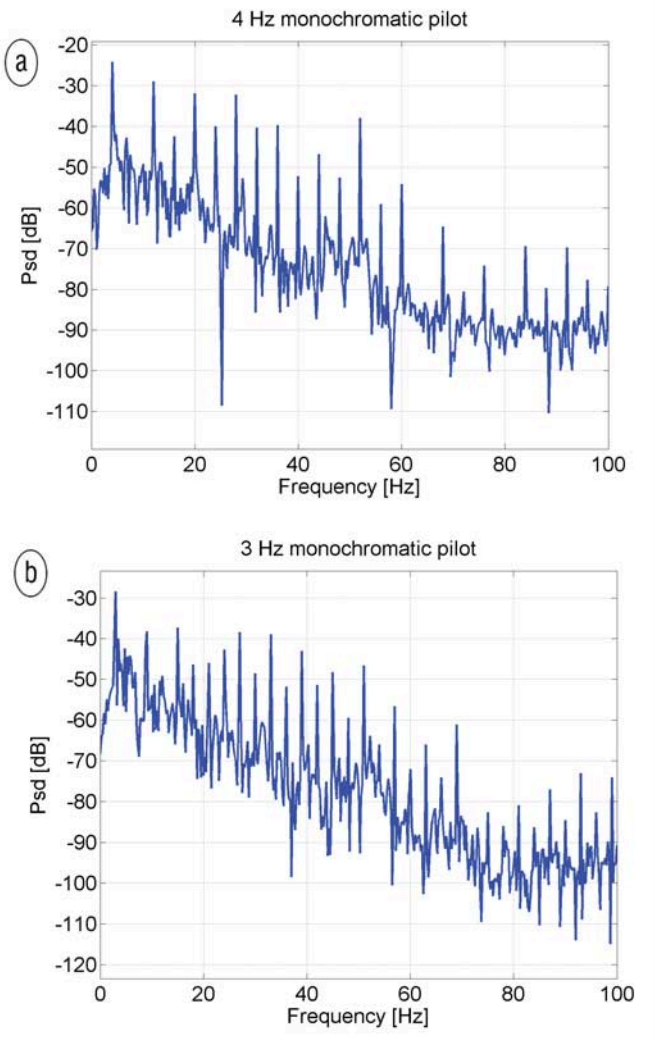

Figure 8. Power-spectral densities of the vertical component of the downhole data recorded during monochromatic sweep tests. (a) 4 Hz monochromatic sweep with target fundamental force of 24 000 lbf (106752 N). (b) 3 Hz monochromatic sweep with target fundamental force of 16 000 lbf (71168 N).

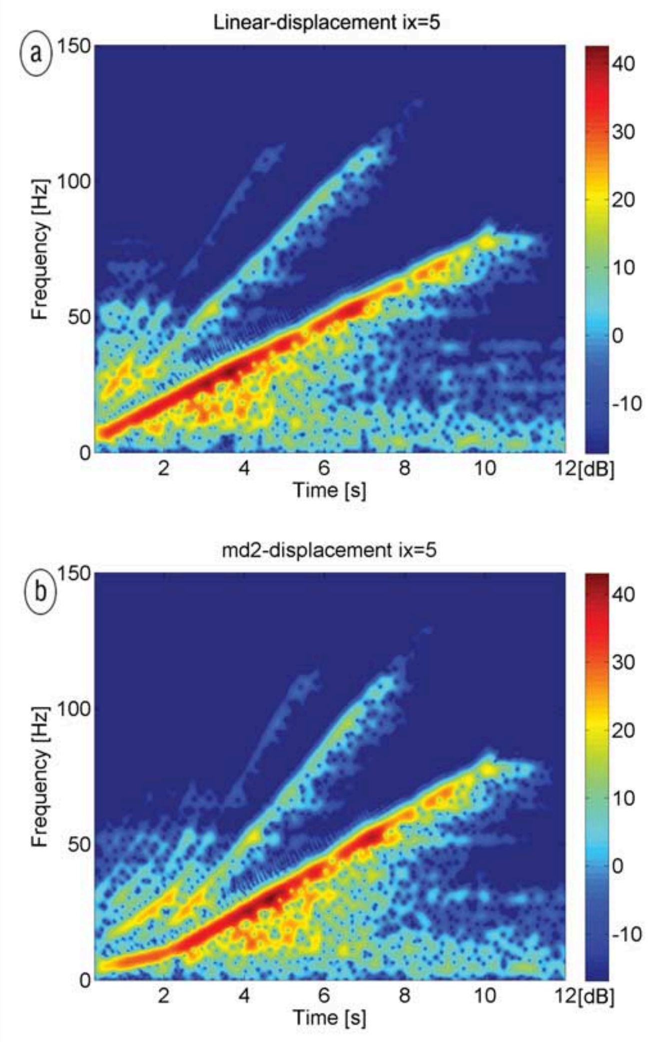

Figure 9. Borehole seismic experiment. Time/frequency representation of the uncorrelated data acquired at the same depth level (730 m) using a linear sweep (a) and a maximum displacement sweep (b).

monochromatic sweep tests that the odd harmonics were very energetic, as shown in Figure 8.

Because the differences between the linear and the maximum displacement sweep are confined to the 4–9 Hz frequency range and because of the broad band of these sweeps, the early arrivals that contain broadband signals are very similar. The differences in the target frequency range can be assessed by representing the borehole data in the time/frequency domain and by performing a power spectral analysis.

Since the far-field particle displacement is, in the absence of shear stress at the surface, proportional to the ground force (e.g., Baeten and Ziolkowski, 1990), it is useful to transform the borehole data from the original acceleration to the displacement domain. Figure 9 shows the time/frequency representation of the uncorrelated displacement data acquired at the deepest level (730 m) for both the linear sweep and the maximum displacement sweep. The response of the Earth's interior to the fundamental and harmonics of the vibroseis signal is clearly visible. The maximum displacement sweep front end, which can be clearly tracked, denotes that the low frequencies generated by the vibrator have been recorded downhole.

Spectral analysis of the borehole data up to about 9 Hz can be carried out without separating the harmonics. The energy of the third harmonic, which is the most critical, falls in fact above 9 Hz. The time-frequency representation of the borehole data (Figure 9) does not show any subharmonics. The power spectral analysis shown in Figure 10 highlights an uplift obtained with the maximum displacement sweep of about 6 dB at 6 Hz, which is consistent with what is observed with the ground-force measurements.

Conclusions. The signal processing community has been working on sweep design for at least a half-century. The theoretical progress made has been huge. However, we have demonstrated that further progress, which is of immediate benefit in seismic exploration, can be made if the peculiar characteristics of modern seismic vibrators are explicitly incorporated in the sweep design procedure.

Maximum displacement is a new sweep design method that enhances the low-frequency content of vibroseis data by optimally designing the drive force and the variable sweep rate, taking into account the vibrator mechanical and hydraulic specifications. This method, unlike standard methods, incorporates the geophysical requirements and the

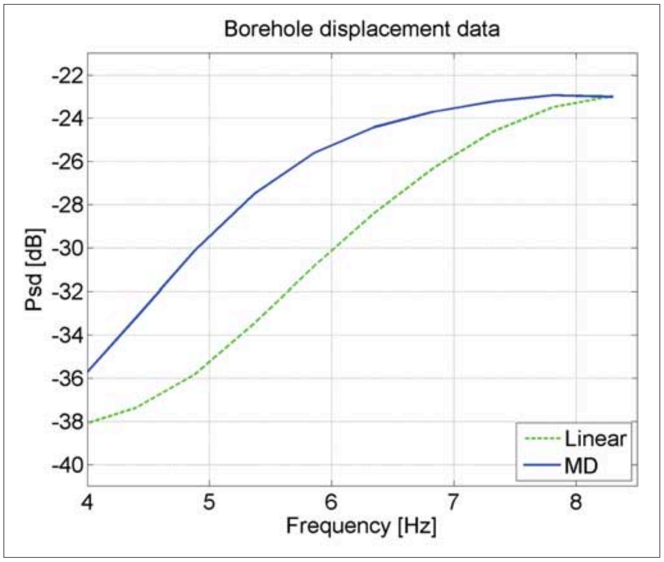

Figure 10. *Borehole seismic experiment. Power spectral analysis of the vertical component of the uncorrelated particle displacement data acquired with a linear and a maximum displacement sweep.*

vibrator specifications. It does not require input parameters such as taper length and the variable sweep rate, whose optimal values depend on the vibrator available in addition to the geophysical requirements. The signal transmitted to the subsurface by maximum displacement sweeps is, to a large extent, independent of the ground elastic properties.

The theoretical advantages of using seismic vibrators with elevated hold-down weight have been reviewed and experimentally verified during several field experiments. The effective estimation of harmonic noise, which any hydraulic vibrator generates, enables the comparative analysis of only the fundamental component of the ground forces for all the sweeps used during the tests. We have shown that the 80 000-lbf (353 000 N) vibrator shaking a maximum displacement sweep generates substantially more fundamental energy than a 60 000-lbf (264 000 N) vibrator in the entire frequency range.

The processing of surface seismic data acquired with an 80 000-lbf vibrator shaking linear and maximum displacement sweeps has highlighted the improved signal-to-noise ratio that can be obtained on deep targets by using the maximum displacement sweep. Borehole seismic data show that the enhancements obtained with maximum displacement sweeps at the vibrator location are preserved at large distances from the baseplate.

The signal-to-noise ratio improvements that can be obtained at low frequencies with maximum displacement sweeps are expected to significantly improve a number of land-seismic applications such as acoustic impedance inversion, imaging beneath high-velocity formations, and velocity analysis in geophysically complex areas.

Suggested reading. *The Vibroseis Source* by Baeten and Ziolkowski (Elsevier, 1990). "Enhancing the low-frequency content of vibroseis data" by Bagaini (EAGE 2007 *Extended Abstracts*). "Systems and methods for enhancing the low-frequency content in vibroseis acquisition" by Bagaini et al. (U. S. Patent 7327633). *Elastic Waves in Layered Media* by Ewing et al. (McGraw–Hill, 1957). "The dispersion of surface waves on multilayered media" by Haskell (*Bulletin of the Seismological Society of America*, 1953). "A method of seismic surveying with overlapping shot times" by Jeffryes (U. K. Patent 2 387 226, 2002). "Method and apparatus for increasing low-frequency content during vibroseismic acquisition" by Jeffryes and Martin (U. K. patent 0415518.0, 2003). "Seismic attenuation of Atlantic margin basalts: Observations and modeling" by Maresh et al. (GEOPHYSICS, 2006). "In-situ shear-wave velocity from spectral analysis of surface waves" by Nazarian and Stokoe (8th Conference on Earthquake Engineering, 1984), "A moving coil dynamic accelerometer" by Obuchi and Fujinawa (EAGE 1991 *Extended Abstracts*). "Vibroseis signals with prescribed power spectrum" by Rietsch (*Geophysical Prospecting*, 1977). "Seismic vibrator control and the downgoing P-wave" by Sallas (GEOPHYSICS, 1984). "Efficient waveform inversion and imaging: A strategy for selecting temporal frequencies" by Sirgue and Pratt (GEOPHYSICS, 2004). "Extending the vibratory envelope: How low can we go?" by Wei (EAGE 2007 *Extended Abstracts*). TLE

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