Vibroseis equipment for efficient low-frequency generation and high-productivity operations

Nicolas Tellier[1*], Gilles Ollivrin[1] and Daniel Boucard[1] present the implications of generating low frequencies for productivity and equipment capability and discuss how modern vibroseis solutions address this challenge.

Extending the recorded seismic bandwidth has become an increasingly prevalent trend in the industry, for the clear benefits this approach provides for seismic imaging: reflections with reduced sidelobes, improved vertical resolution, more accurate velocity models and inversion providing better reservoir characterization. Such benefits have been underlined by many authors (Baeten, 2013; Mahrooqi, 2012; Plessix, 2010). In vibroseis, broadband means pushing the conventional 8-80 Hz frequency range sweep lower and higher. The low-frequency aspect has been particularly addressed in recent years, with improvements mainly achieved in:

- The mechanical design of vibrators.
- The sweep definition, which can be customized to fit the physical limitations of vibrators and ensure that they are used with maximum efficiency.
- The vibrator controllers, which have been adapted to ensure proper sweep generation, control and an accurate QC.

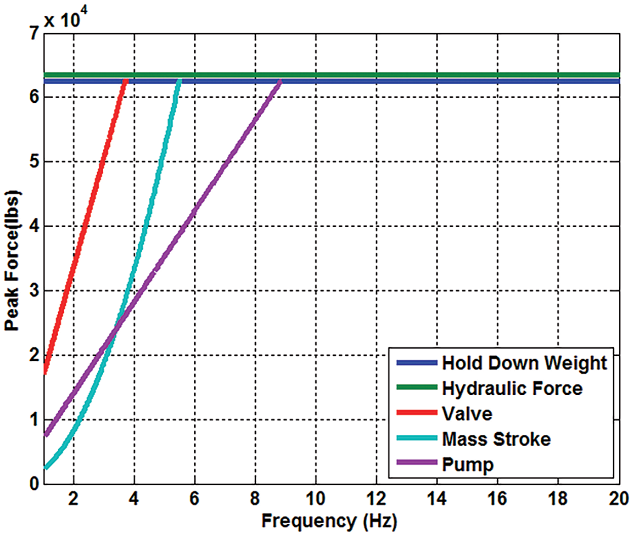

Figure 1 *Physical limitations of a heavy (62,000 lbf) vibrator at low frequency (example for a Nomad 65 Neo). The maximum output is limited by the mass stroke limitation (for example, 32,000 lbf at 4 Hz).*

These improvements make it possible to push vibrators as close as possible to their low-frequency mechanical limitations in order to perform sweeps starting as low as 1 Hz.

However, the generation of extra low frequency bandwidth may be quite impactful for productivity, as it generally requires a lower drive level and hence a slower sweep rate. This article presents the implications of generating low frequencies in terms of both productivity and equipment capability and then discusses how modern vibroseis solutions efficiently address this challenge. Dramatic results are obtained, since, in addition to improving the low-frequency generation and subsequent imaging, productivity benefits of up to 76% may be expected.

The low frequency issue

Conventional vibroseis equipment performance

Vibroseis equipment has traditionally been optimized for the 8-80 Hz sweep bandwidth, used on most seismic projects.

Vibrator's mechanical and hydraulic factors, which limit the emission of low frequencies, have been identified (Sallas, 2010) as:

- Mass stroke, i.e., the mass maximum displacement with regards to the piston;
- Pump flow, i.e., the pump's ability to meet the strong flow oscillations imposed by low frequencies;
- Valve stroke, equivalent to the mass stroke for the valve driving the vibration.

Nonetheless, by adopting a relevant design and size for the hydraulic accumulators, the pump and valve limits are pushed back; the mass stroke becomes the key limitation factor (Figure 1).

Vibrator electronics were also optimized for this 8-80 Hz frequency range. Although a less known and less visible vibroseis equipment, its role is nonetheless essential as it generates the sweep pilot, and adapts this theoretical ideal input into a signal that drives the servovalve and hence the whole vibration. Vibrator electronics must also provide exploitable QC and ensure high repeatability.

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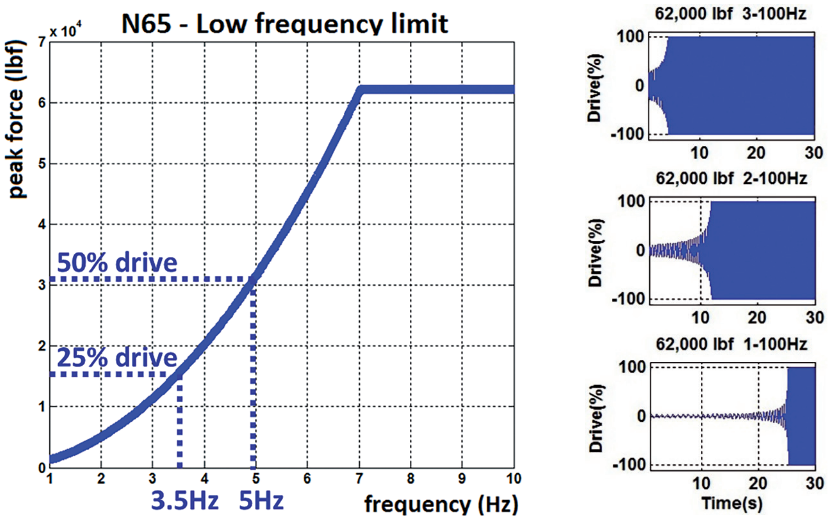

Figure 2 *(Left) To preserve energy, sweeping at 5 Hz (50% drive) takes 4 times as long as at full-drive; sweeping at 3.5 Hz (25% drive) takes 16 times as long. Data for a Nomad 65 vibrator. (left) Influence of the start frequency on low-frequency ramp-up duration: 4 s from 3 Hz (up), 12 s from 2 Hz (center), 25 s from 1 Hz (bottom).*

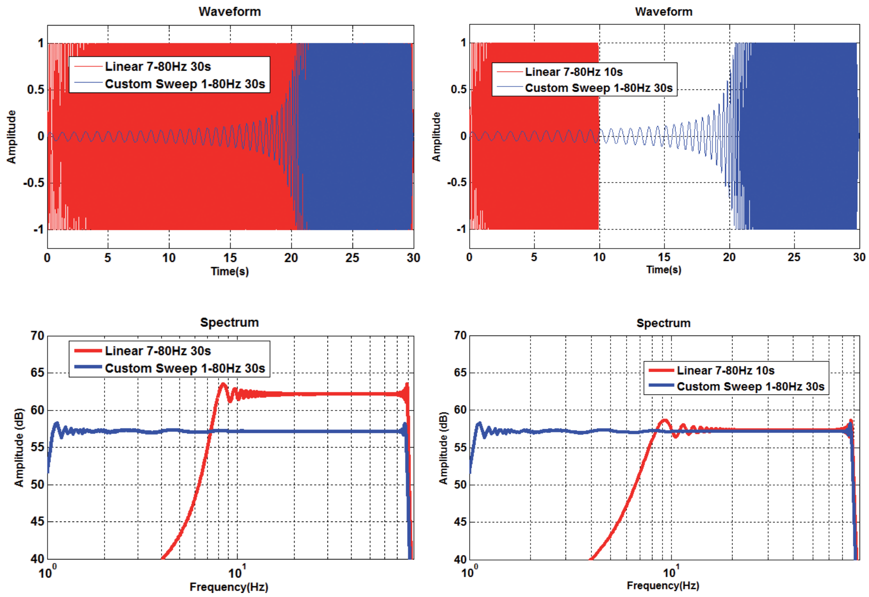

Figure 3 *Consequences of extending the bandwidth toward the low frequencies: (Left) same sweep duration impacts signal amplitude; (Right) longer sweep preserves amplitude but impacts productivity.*

Productivity issues

Until recently, manufacturer specifications in the rated frequency section only specified the full-drive start frequency. However, as shown in Figure 1, the physical limitations of vibrators make it possible to sweep at lower frequencies, but not at full drive. Thus, 'low-dwell' sweeps were developed (Bagaini, 2008; Sallas, 2010). Using a non-linear taper up to the full-drive start frequency, these sweeps fit vibrator limitations and make it possible to start operating from 1 Hz, with a reduced drive level.

The main issue with such tapers is the preservation of a flat spectrum on the full sweep bandwidth. Indeed, reducing the drive while preserving the emitted energy requires using a slower sweep rate, i.e., dwelling for a longer time on the relevant frequencies. Thus, for a given frequency, the sweep duration has to be increased by the square of the drive reduction. Compared to a 100% drive, emitting a frequency with a 50% drive requires spending four times as long on this frequency; a 25% drive requires spending 16 times as long. As a consequence, the time spent on the taper may represent a significant amount of time (Figure 2), which will either increase the sweep overall duration, or for a given sweep length reduce the time spent on the full drive range, thus reducing the emitted associated energy (Figure 3).

Equipment improvements for low-frequency emission

Vibrators

Vibrator designs were reviewed to improve their low-frequency capability. The vibrator's full-drive start frequency is defined by formula (1), which indicates that the start frequency can be

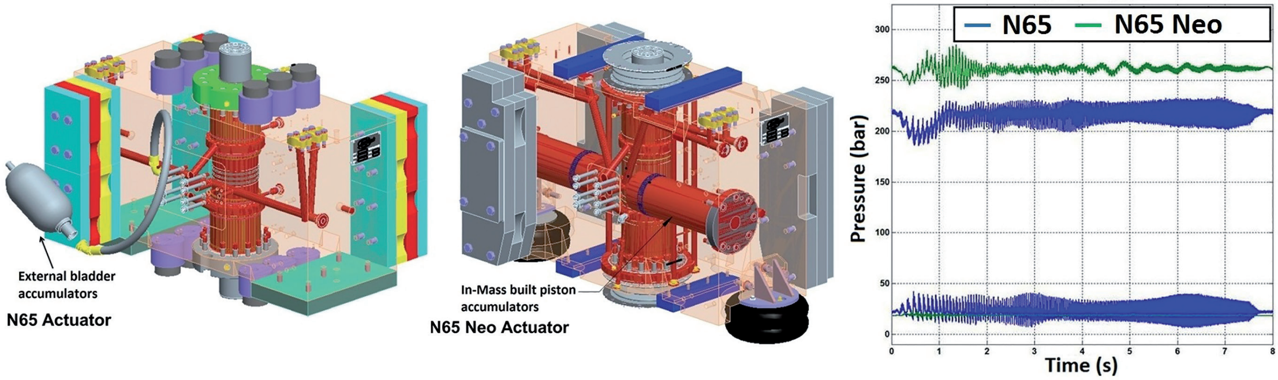

***Figure 4** Reaction mass designs and their influence on hydraulic pressure stability at low frequency. Sweep 3-30 Hz, 8 s, 40%.*

lowered by increasing the reaction mass weight and the usable stroke, i.e., the reaction mass maximum displacement. These features were adapted in consequence.

$$F\min = \frac{1}{2\pi} \times \sqrt{\frac{Min(HPF, HDW)}{Mm \times \frac{Usable\,stroke}{2}}} \qquad (1)$$

Another important factor is the hydraulic differential pressure (high pressure minus low pressure). A pressure drop is commonly observed at low frequencies, as the large reaction mass displacement creates a high demand of hydraulic fluid (Sallas, 2010). When dwelling at very low frequency, an insufficient differential pressure leads to a pressure drop that prevents the necessary flow to the servovalve, which compromises the vibration capability. Low-frequency vibrators therefore require a higher hydraulic differential pressure.

The low-frequency, high-amplitude mass oscillations imply the same effect on hydraulic pressure, which needs to be stabilized. This can be achieved by installing the accumulators as close as possible to the servovalve (Wei, 2011), which prevents the important pressure transients related to the usual membrane-type accumulator set up (linked to the servovalve by relatively long hoses). Mass with integrated piston accumulators make it possible to minimize this distance and the related pressure transients (Figure 4), and has proven to be a strong and reliable design.

These modifications enable the reduction of the vibrator full-drive frequency from around 7 Hz for heavy vibrators down to around 5.5 Hz. Besides improving the vibration performance and subsequently the imaging quality, this 1.5 Hz difference proves to have a strong impact on productivity, as described later. Table 1 summarizes the main modified features for two heavy vibrators.

Vibrator electronics

In addition to vibrator low-frequency capabilities, vibrator electronics should be able to control the non-linear taper of the low-frequency sweep. The vibrator electronics should indeed be able to generate the accurate low-dwell ramp-up, while maintaining a low phase error, a low distortion and an exploitable QC in a repeatable manner (Tellier, 2014).

Generating useful low frequencies

The classic feedback loop that controls and corrects the phase only at the Ground Force zero-crossing becomes inefficient at low frequency due to the increasing sweep period and the noise level. Thanks to full digital control based on a numerical vibrator model (Boucard, 2010), the vibrator electronics' servo-control is designed to perform a pursuit command to drive the Ground-Force as close as possible to the Pilot every 0.25 ms. Since non-linearities are included in the vibrator model, the commands take them into account to provide a non-linear input that reduces harmonic distortion. This is critical at low frequencies, particularly below

	62,000 lbf vibrator Conventional	62,000 lbf vibrator Enhanced actuator
Reaction Mass Weight	4,082 kg	4,700 kg
Mass Stroke	7.62 cm (3 in.)	10.12 cm (4 in.)
Piston Area	133.4 cm²	112.6 cm²
Differential pressure	200 bar	247 bar
Full drive start frequency	7 Hz	5.4 Hz

***Table 1** Comparative specifications for two 62,000 lbf vibrators: the Nomad 65 and its new low-frequency model, the Nomad 65 Neo.*

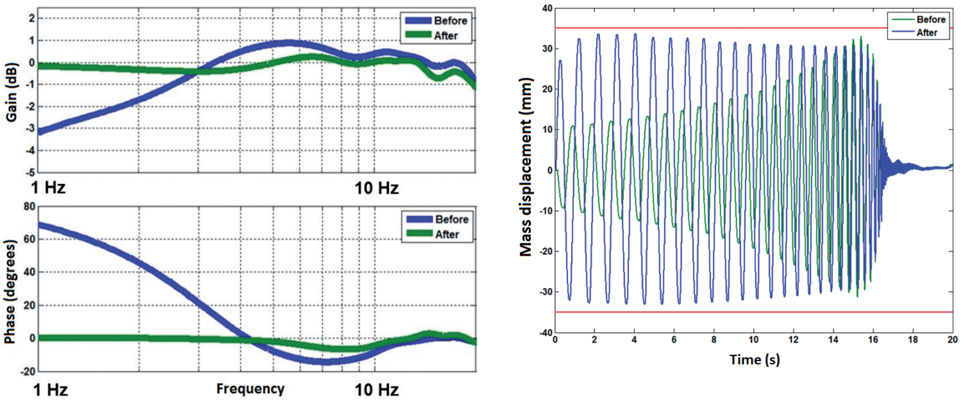

Figure 5 *(Left) Gain and phase correction on a 1-20 Hz window: the green curve after controller correction indicates a great improvement in sweep control in low frequencies compared to the blue curve. Field tests with Nomad 65 vibrators controlled by VE 464; (Right) Mass displacement before and after correction, low-dwell sweep 1-80 Hz, 20s, 80%, Nomad 65.*

3-4 Hz where all non-linearities and the associated distortion increase. However, because non-linear tapers decrease the sweep rate, correlation is able to reject this distortion at larger negative times.

Gain and phase can be problematic in very low frequencies (<4 Hz), with notable discrepancies between desired signal and real output. Essential corrections on controllers in low frequencies were achieved (Figure 5, left), with gain errors brought down from 60% below 3 Hz to negligible, and phase error reduced from 70° to a few degrees after correction. This accurate low-frequency gain and phase control enables:

- A sweep closer to the pilot;
- Full use of the vibrator's mass stroke capability (Figure 5, right);
- Better signal repeatability;
- An optimal sweep design with shorter taper.

Effective QC

Low-frequency QC used to be problematic in the field and in practice was not performed at all for frequencies below around 4 Hz, due to the common practice of averaging mass and baseplate accelerometer values on a 0.5 s window (2 Hz) to compute a Ground-Force QC every 0.5 s. This process does not allow several signal periods to be included in the QC computation. It meant that below 4 Hz, values do not reflect the real behaviour of ground excitation. A new approach consists of defining larger computation windows. Simulations confirmed by field tests (extracts in Figure 6 with 0.5 and 1 s windows) allow us to define an optimal compromise of overlapping 1 s computation windows with QC value outputted every 0.5 s, as too large windows produce irrelevant QC's.

In addition, due to the low and increasing drive, low-dwell QC's are in practice difficult to interpret and poorly representative and exploitable. The use of normalized QC's with the low-dwell ramp-up QC resized to the same scale as full-drive QC's makes it possible to perform effective and legible field QC's from the very start of the sweep.

Field pre-production simulations

Custom sweeps designed for low-dwell optimization to fit vibrator mechanical constraints can be accurately fine-tuned before the start of field operations, and therefore validated for optimal production. Such simulations enable us to take into account factors that would not otherwise be predicted, such as the vibrator's condition.

In practice, different behaviours can be observed at very low frequency on two identical sweeps differing in their initial phase: a 0° initial phase of a custom-designed low-dwell sweep may indeed exceed vibrator limitations, while the same sweep with a 90° initial phase would not. Such

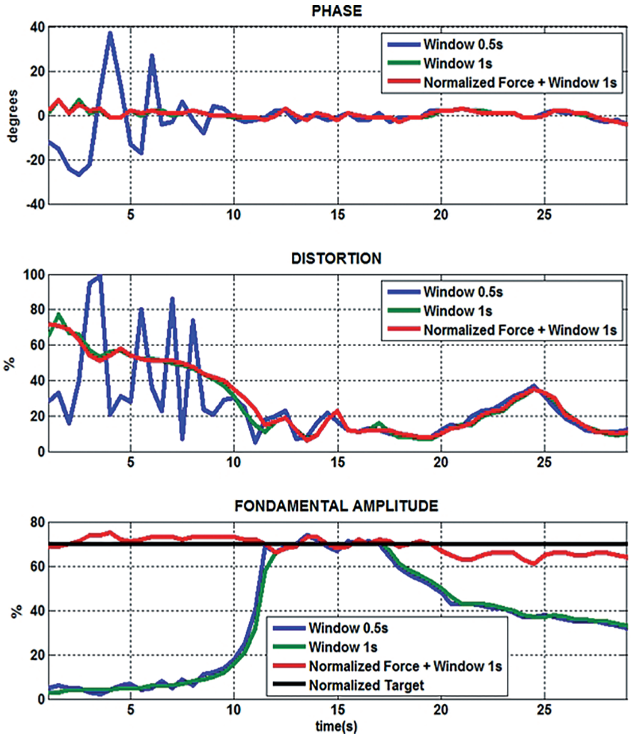

Figure 6 *Comparison of the common 0.5 s and 1s overlapping computation windows on QC's (field tests) with normalized results. QC values are outputted every 0.5 s in both cases.*

pre-production precautions make it possible to emit a given sweep without any unnecessary drive reduction.

Vibrator limitations and initial phases can be easily simulated with tools such as Sercel's CheckSweep, and different sweeps and vibrators compared in different domains. The benefits of custom broadband sweeps can in this way be improved, allowing time-savings in low frequencies and an optimum fit with the vibrator's physical limits.

Low-frequency generation and productivity

Productivity with low-frequency heavy vibrators

In addition to improving the vibration and subsequent imaging quality, the 1.5 Hz difference offered by low-frequency heavy vibrators proves to have a strong impact on productivity (Tellier, 2014): vibrators reach the full drive start frequency more rapidly, and up to this frequency can provide a faster sweep rate.

The sweeps in Figure 7 were designed for the two 62,000 lbf vibrators described previously (the conventional vibrator, and the new low-frequency model, with full-drive start frequencies respectively at 7 Hz and 5.4 Hz). With reference to a 30 s sweep designed for the conventional vibrator, the low-frequency version achieved a reduction in sweep duration which increases as the start frequency decreases: 27s (-10%) from 3 Hz, 22s (-27%) from 2 Hz and 14s (-53%) from 1 Hz. As indicated by the spectra, the energy radiated by the two vibrators remains equivalent in amplitude and bandwidth.

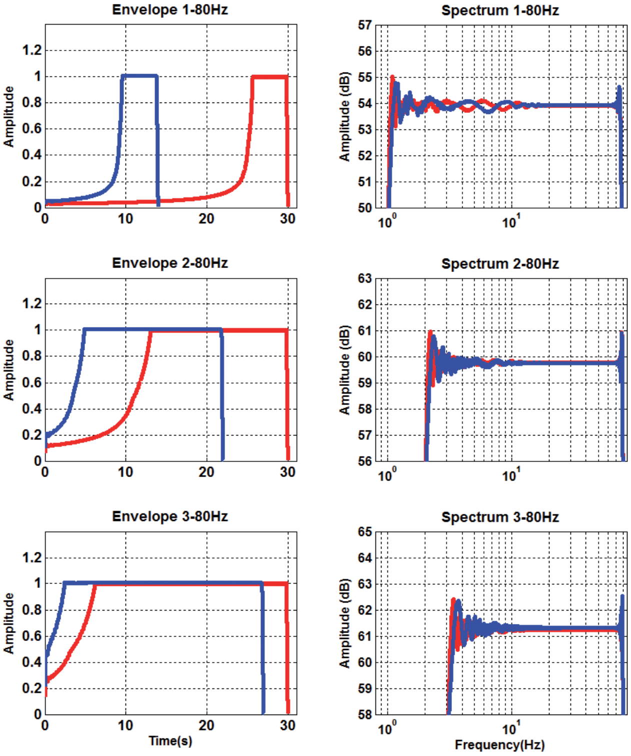

Figure 7 *Compared performances between (red) a conventional 62,000 lbf vibrator (Nomad 65) and (blue) its low-frequency model (Nomad 65 Neo): custom sweeps 1-80 Hz, 2-80 Hz, 3-80 Hz, drive 80%. Duration is set to 30s for the conventional vibrator, and adapted to the other vibrator to output an equivalent spectrum.*

Productivity with super-heavy vibrators

Until recently, super-heavy (80,000 lbf) vibrators have been regarded mainly as vibroseis sources for single-source high-density operations in open areas. Their use has been limited until now: even though an increasing number of operators require either heavy (around 60,000 lbf) or super-heavy vibrators in their bidding process, the fact that sweep parameters (especially drive level and length) are only confirmed during the crew start-up phase does not make it beneficial for contractors to choose the super-heavy option.

However, the 80,000 lbf vibrators may be considered otherwise. Fitted with a heavier mass and a larger mass stroke, these vibrators are natural candidates for low frequencies, with current vibrators on the market offering full-drive start frequency of 5 and 5.5 Hz. This frequency

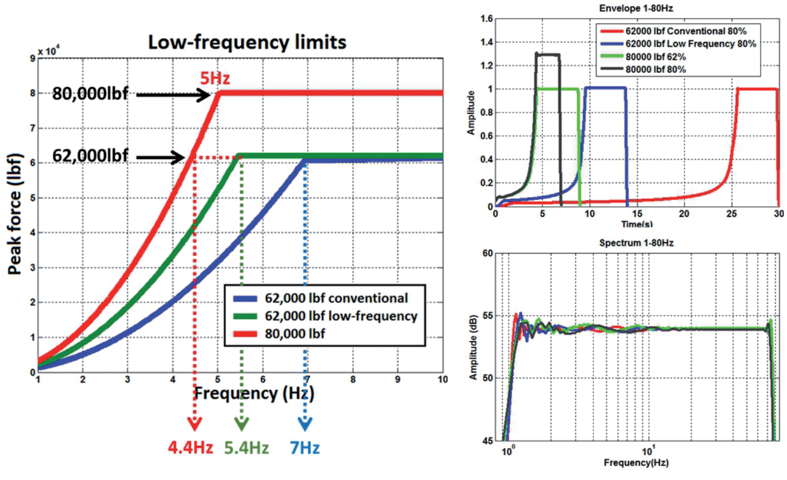

Figure 8 *(Left) Comparative low-frequency performances of two heavy vibrators (N65 and N65 Neo) and a super-heavy one (N90) used with full output and an output equivalent to heavy vibrators. (Right) Corresponding 1-80 Hz sweep shapes. Sweep duration varies from 30 s to 7 s. Energy emitted is identical in all four cases.*

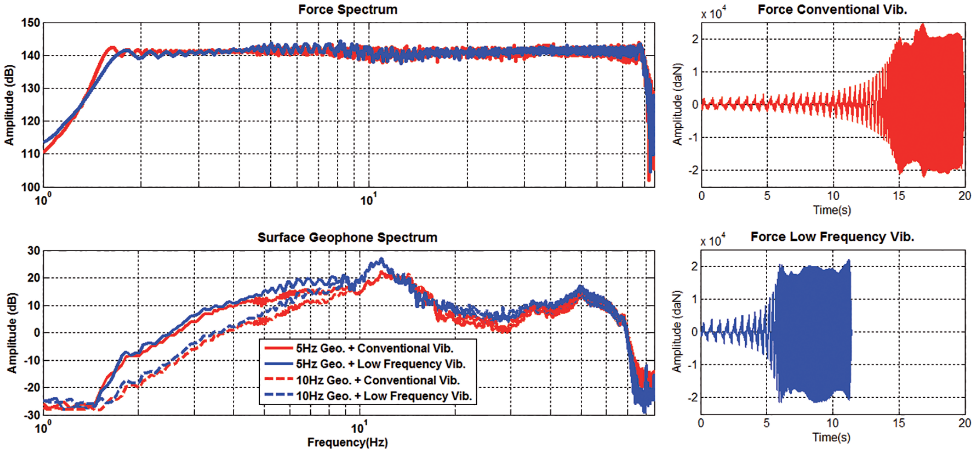

Figure 9 Sweep shapes, forces, and surface data spectra of two 1.5-75 Hz, 80% drive sweeps generated by a VE464 (without enhanced low-frequency control) for a Nomad 65 vibrator (20 s, red) and its low-frequency model, the Nomad 65 Neo (11.5 s, blue), for two lines of sensors: 5 Hz (continuous lines) and 10 Hz (dotted lines).

can be significantly lowered if the drive is reduced to make it comparable to 62,000 lbf vibrators (e.g., 4.4 Hz for a Nomad 90).

The left-hand panel in Figure 8 displays the full drive start frequencies of a Nomad 90 vibrator, using either its 80,000 lbf full capability, or a 62,000 lbf output. The right-hand panel superimposes on the results displayed in Figure 7 (sweep starting from 1 Hz) those obtained with this vibrator, with the aim of generating an emitted energy spectrum identical to the other two vibrators. At a 62% drive (equivalent to 62,000 lbf at 80%) the 80,000 lbf vibrator sweep's full-drive start frequency is decreased to 4 Hz: sweep duration is reduced to 9 s (-70%). Using the same vibrator at 80% of 80,000 lbf allows a further reduction in the sweep to 7s (-76%). In both cases, the gain in sweep duration is tremendous and opens the way to new levels of productivity.

Some limitations nonetheless have to be taken into account: a reference to a shorter than 30 s sweep (e.g. 12 s) for the conventional 62,000 lbf would have led to very short sweeps (less than 3 s) that may not have allowed pressure to build up and stabilize in time, with an impact on the low-frequency distortion level and the sweep bandwidth. The consequence of sweep duration is also subject to discussion, and has less impact on productivity in the case of slip-sweep operations (Egreteau, 2009, Mahrooqi, 2012, Meunier, 2012), unless more vibrators are used for the acquisition

Field tests

Field tests were conducted in January 2014 at the Bonnefont testing facilities, in the south west of France. One of the objectives was to validate the seismic data content obtained by the two 62,000 lbf vibrators using different sweep durations. Two 2D lines of 100 single-geophone receiver points each were deployed, with 5 Hz and 10 Hz geophones (SG-5 and SG-10) spaced at 5 m intervals. Note that vibrator electronic low-frequency features described above were not implemented at the time of the test. Figure 9 displays the shape of the two sweeps used, the corresponding recorded forces, and the shot point spectra (after correlation) obtained for each line on the 60 geophones the most remote from the sources.

The spectra of the emitted ground force (given by the weighted sum obtained with vibrator accelerometers) are equivalent for both vibrators. Shotpoint records confirm signal consistencies, with equivalent spectra. A clear boost in low frequencies on the 5 Hz geophone line helps to recover amplitude in the lowest 10 Hz frequency range. The energy emitted and recovered in the two cases is similar, while use of the low-frequency vibrator produces a 43% time reduction.

Conclusion

It has proved to be possible to push back the low-frequency limits of vibrators by completely reviewing their design and using appropriate custom sweeps. They offer a lower full-drive start frequency, and a higher sweep rate up to this frequency. This enables a strong reduction in the low-dwell sweep duration. Vibrator electronics have also evolved to accompany this new vibrator capability. They offer accurate low-frequency phase and gain control and QC, which makes it possible to optimize the generation of low-dwell sweeps and use these vibrators in an optimal way.

Nowadays, the new generation of vibrators is still commonly considered:

- In the case of heavy (60,000 lbf) low-frequency ones, as sources improving the low-frequency content and quality of seismic imaging;
- In the case of super-heavy ones (80,000 lbf), as sources for single-vibrator, high-density acquisition in open areas.

However, they should both be considered as sources which enable high-productivity performance for very low-frequency acquisition.

Acquiring extra octaves, which are very beneficial for improving inversion and vertical resolution, can be performed at a lower cost. As the industry becomes increasingly focused on broadband seismic acquisition, similar issues are at stake for high frequencies. Vibroseis equipment will accompany this new paradigm.

Acknowledgments

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