Practical solutions for effective vibrator high-frequency generation

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Summary

Extending the range of frequencies available in the seismic dataset is widely recognized for its contribution to imaging quality so extra octaves of signals have to be generated. However, vibrators that are much appreciated for their low VP cost and high productivity used to have limited capability for these newly expected ranges of frequencies. Numerous solutions were successfully developed in recent years to address low frequencies. The challenge is more difficult for high frequencies, where vibrator behavior is strongly dependent on ground properties. This, added to the stronger absorption and attenuation of short wavelengths, make operators rather reluctant to extend their sweep in the high frequencies. This abstract presents and discusses a few practical and effective solutions to push the frequencies emitted by vibrators higher. A hydraulic peak force exceeding the hold-down weight, stable hydraulic pressures, and a stiffer baseplate prove to be reliable vibrator design solutions. The proper baseplate displacement measurement is also paramount to providing reliable QC that avoids measurement artifacts and faithfully reflects the down-going signal. Lastly, the use of high-dwell sweeps, customized in high frequency with a lesser amplitude, is a simple way to properly emit frequencies that would have otherwise made vibrators reach their physical limitations.

Introduction

Numerous efforts have been achieved to extend the vibrator's conventional 8-80 Hz sweep bandwidth. Low frequencies have been widely addressed in the recent years with innovations concerning mainly equipment – low-frequency vibrators and geophones, low noise floor digital sensors – and processing algorithms. Publications are numerous; the use of low frequencies is progressively spreading and is already becoming a standard in several regions (Mahrooqi, 2012, Winter 2013). High frequencies remain a puzzling issue: their proper emission is strongly dependent on ground types and vibrator behavior cannot be modelled as easily as for low frequencies. In addition, they are subject to quick absorption. However, their contribution to seismic imaging is paramount for the temporal resolution they yield; they are even compulsory for projects targeting shallow or thin layer detection. Most sensors already have the capability to record high frequencies up to a few hundred hertz, far above the exploration industry requirement – especially digital sensors whose sensitivity increases with frequency. The recording issue thus mainly concerns the geometry that has to be densified to avoid aliasing when recording the shorter wavelengths, and the preferential use of single source and single receiver. This abstract focuses on high-frequency generation: how can vibrator physical limitations be overcome, and what solutions do we have to emit high frequencies with the highest possible fidelity? Several practical and truly effective solutions are presented and discussed.

Higher hydraulic force

A common vibrator design assumption is that its Hydraulic Peak Force (HPF) shall roughly equal the Hold Down Weight (HDW). Vibrators actually show different behaviors when sweep frequencies increase and the contributions of mass and baseplate to the weighted sum ground force ($GF = Mass_{mass} * Acc_{mass} + Mass_{baseplate} * Acc_{baseplate}$) (Formula 1) differ:

- At low frequencies, the mass and baseplate accelerations are roughly in phase: the contribution of the heavier mass prevails.
- When the sweep frequencies increase, a phase shift appears between the mass and baseplate while baseplate acceleration increases, but vibrator electronics adapts the mass acceleration to keep a constant ground force.
- At higher frequencies, the significant phase shift causes the baseplate contribution to increasingly counter that of the mass while hydraulics reaches its limit: mass acceleration cannot be increased, and the ground force starts decreasing. When a 180° phase shift is reached, ground force amplitude may thus drop far below expected target.

A solution consists in designing vibrators with HPF exceeding their HDW (Tellier 2015). At low frequencies, vibrator electronics regulate the HPF to prevent the vibrator from "bouncing." At high frequencies, the additional hydraulic capability enables increasing the mass

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contribution to the ground force and thus keeps the latter on target for an extra bandwidth.

Hydraulic pressure stability

The generation of high-quality, high-frequency vibrations requires hydraulic pressure stability, for two main reasons. Firstly, the high-frequency quick mass oscillations induce important hydraulic pressure oscillations that must remain within the vibrator physical capability. Secondly, on a vibrator servo-control based on fixed theoretical pressures, stable pressures enable generating vibrations as close as possible to the servo-control model. On recent vibrators, the pressure stability is enabled by hydraulic accumulators fitted as close as possible to the servovalve: it reduces the pressure transients, particularly important at both low and high frequencies. The difference with the conventional external accumulators design in use until recently is significant (Figure 1). The piston-type accumulators used internally also prove to be more reliable than the membrane-type external accumulators, especially when used in Arctic conditions.

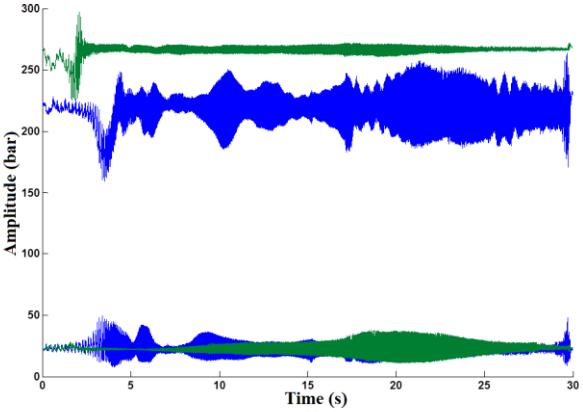

Figure 1 – Hydraulic pressure: external membrane–type (blue) and internal piston-type (green) accumulators, sweep 2-200 Hz, 30 s, 70%, 62,000 lbf vibrator.

Baseplate stiffness

Baseplate stiffness is a recognized issue for high-frequency generation (Ley 2006). When the sweep frequencies increase, the baseplate is more subject to flexure. Baseplate accelerometers will record this flexure and incorporate it into the weighted sum ground force (Formula 1): flexure will then be interpreted as a ground force contribution. An acceptable vibro QC-ed ground force may subsequently be produced, but with poor correlation as per the measurements of signal effectively transmitted to the ground (performed for example with a VSP or with a load cell testing bench installed below the baseplate).

However, setting accurate specification on baseplate stiffness is not an easy matter and up until now, manufacturers did not provide this information: in dynamic activity, baseplate resonance node and antinode frequencies do indeed strongly vary with ground types and the way vibrators are coupled with the ground. A second-best option is to provide baseplate moments of inertia, i.e., a representation of the baseplate stiffness in static.

To illustrate this, a conventional baseplate was compared to a stiffer one having a much higher transversal moment of inertia (Figure 2), on a load cell test bench. Good correlation was observed between moment of inertia and signal fidelity (Figure 3). When moment of inertia is higher, the signal can be effectively emitted in higher frequencies (a and b, top, solid blue line). The ground force QC (a and b, top, solid red line) provides a better representation of this signal, even if discrepancies remain. Lower phase (a and b, bottom, solid blue line) and distortion (not displayed) are also observed.

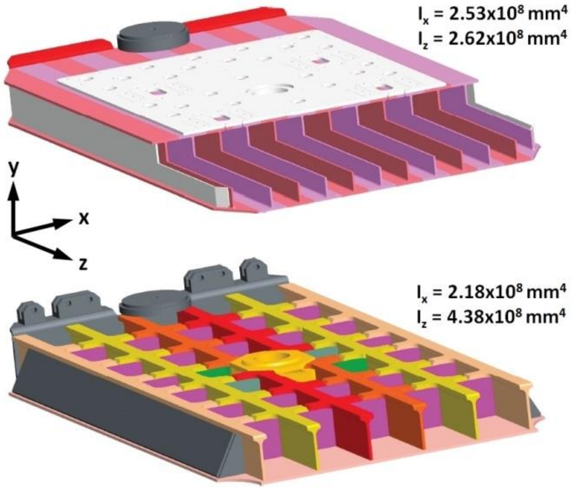

Figure 2 – Standard (top) vs. stiffer baseplate (bottom); longitudinal (I_x) and transversal (I_z) moments of inertia.

Manufacturers currently have the know-how to produce the lightest and stiffest possible baseplates. But this comes with an extra cost induced by the materials and manufacturing technologies that today all end-users are not ready to accept.

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Baseplate displacement measurement

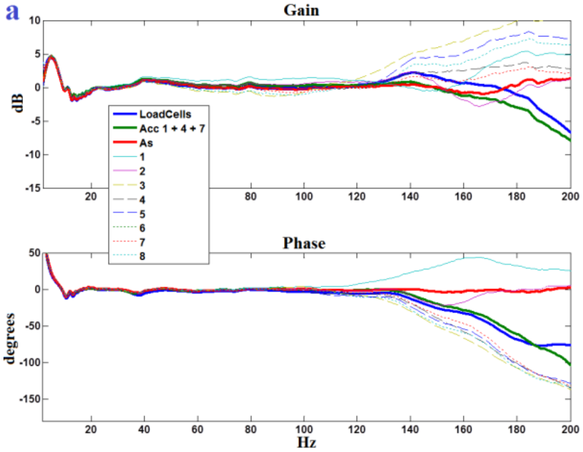
A corollary of baseplate limited-rigidity (including the improved ones) is that flexure will affect accelerometers located at different baseplate positions differently. To illustrate this phenomenon, results of field tests performed on a concrete pad with nine different accelerometer locations are displayed in Figure 3. While results are equivalent at low and mid frequencies, significant discrepancies in ground force amplitude and phase can be observed above 120-140 Hz. The stiffer baseplate reduces these differences, but they still remain important.

The baseplate accelerometer position is then essential for obtaining QC that represents the true emitted signal (Figure 3, solid blue lines). Manufacturers usually propose the optimum position (solid red lines), but vibrator electronics offer features that improve the QC fidelity:

- The use of a proper combination of accelerometers (solid green lines).
- The use of a QC-filtered mode, based on estimated states, instead of raw measurements, and derived from a Kalman filter (Boucard and Ollivrin, 2010).

Unfortunately, such solutions are still rarely employed on the field.

Note nonetheless that stiffer baseplate design and proper acceleration measurements will not fully compensate poor baseplate coupling conditions.



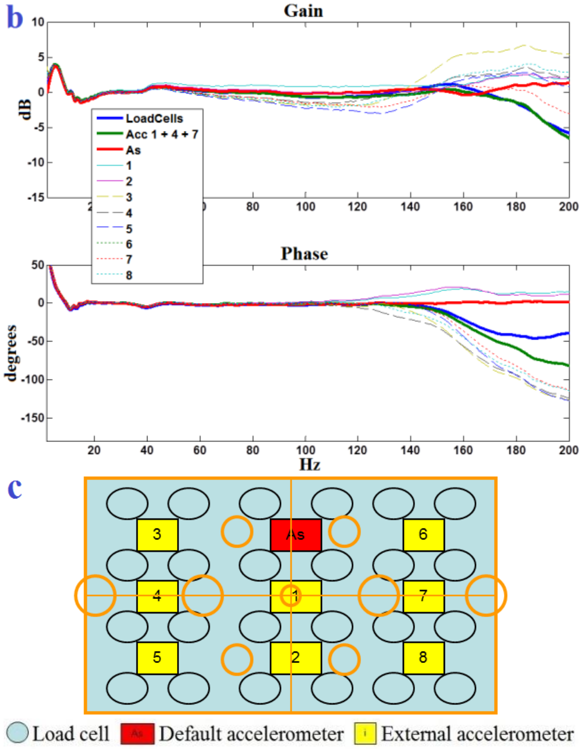


Figure 3 – Ground force amplitude and phase for nine different baseplate accelerometer positions for (a) conventional and (b) stiffer baseplate. Test bench scheme (c).

High-dwell sweep

Low-dwell sweeps have been widely recognized as a powerful means to extend vibrator bandwidth toward low frequencies. However, their equivalents for high frequencies ("high-dwell" sweeps) are rarely used: vibrators usually operate at the same drive level regardless of the frequency above the low-dwell taper. The issue is in fact similar at high frequencies: vibrators must keep operating within their physical limitations.

These limitations differ with frequency. Low-frequency generation dependence on ground is negligible: vibrator behavior is widely predictable, equations show a good fit with reality, and optimum sweeps can be accurately designed accordingly (Sallas, 2010). At high frequencies, various other limitations with respect to the ones presented above affect vibrator performance, but the ground remains a major limiting factor: generating high frequencies on soft ground will be far more challenging than on hard ground.

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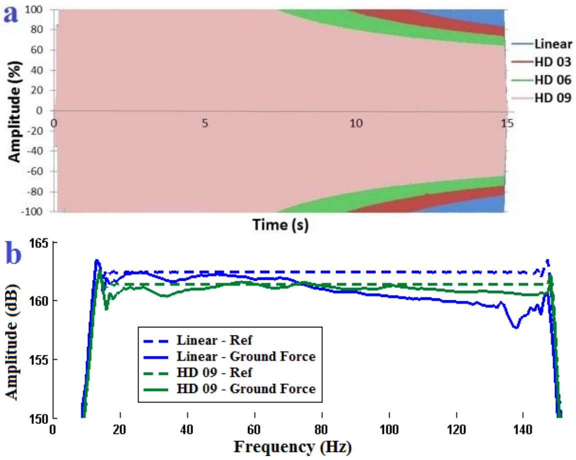
With this consideration in mind, reducing the vibrator output in high frequencies is an effective way to generate sweeps that will not reach vibrator limitations. Figure 4a displays several high-dwell sweep shapes compared to a linear one. These sweeps were used for field tests on relatively soft ground in the south-west of France early 2015. It was observed that the linear sweep was too strong in high frequencies, producing over-pressure warnings (requested pressure exceeding the available one) starting from 58 Hz. This limitation overrun led the vibrator electronics to reduce the ground force output (4b, solid blue line) to preserve the vibrator and maintain low phase and distortion. Strong inter-harmonic noise is also observed (4c, top). High-dwell sweeps enable mitigating these drawbacks, and increasingly so as the attenuation increases: overload warning are less numerous; hydraulic pressures more stable; distortion and inter-harmonic noise weaker (4c, bottom); and ground force more stable, closer to its target (4b, green).

The cost of these high-dwell sweeps when compared to conventional linear sweeps is a slightly smoother amplitude, which can be nonetheless balanced by a longer sweep. For our example with the highest attenuation, the amplitude loss is 1 dB and the time required to overbalance it is 4 s, which is an acceptable compromise for an optimally controlled sweep.

Such sweeps can be designed and tested on the crew during pre-production field tests on ground representative of the operation area by setting the attenuation start frequency and amplitude. Successful examples of sweep-tuning at high frequency have already been reported (Gillot 2005).



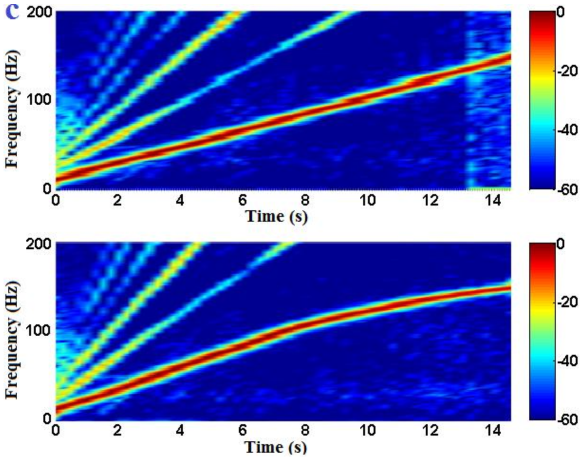


Figure 4 – 10-150 Hz, 15 s, 80% sweep for a Nomad 65 Neo vibrator. (a) Linear vs. high-dwell sweep shapes. Linear vs. strongest attenuated sweep (HD09) comparison: (b) force QC, (c) energy spectra (top: linear, bottom: HD09).

Discussion and conclusion

Several practical solutions regarding vibrator design enable us to improve their high-frequency performance: a HPF superior to the HDW to compensate the reaction mass to baseplate phase shift and subsequent ground force amplitude loss; stable hydraulic pressures; stiffer baseplates; and optimized position of baseplate accelerometer. In addition to the vibrator design achievements, the use of high-dwell sweeps adapted to the ground conditions allows us, as for their equivalent in low frequencies, to generate effectively frequencies, that would otherwise make vibrators reach their physical limits, and to produce a high quality signal.

Increasing the conventional sweep 80-Hz high-end frequency is then within reach: for deep hydrocarbon surveys, sweeping up to 120 Hz is easily achievable and ultimately improves the seismic imaging quality. Seismic projects using such parameters (Seeni 2010) have already been performed, but up until now, there have been very few. Higher frequencies are more subject to attenuation and absorption and shall be considered on a case-to-case basis.

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