Novel P and S wave vibroseis source for high-resolution seismic imaging

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ABSTRACT: A novel engineering seismic source capable of generating both P- and S-wave was developed recently. The vibroseis source is driven by multiple linear synchronous electric motors, providing 1700N (400lbs) peak force. With its wide frequency range and low harmonic distortion this electric vibroseis system produces unseen resolution images. Unique in its kind, multiple sources can be synchronized with unprecedented accuracy to increase the force generated.

Depending on subsurface geological conditions depth of penetration can be up to 500 m for P- and 300 m for S-wave surveys, however high-resolution reflection seismic imaging using S-waves can start as shallow as just few meters below the surface. This makes the system suitable for a wide range of applications ranging from near surface void detection, to structural or stratigraphic investigations. Examples are shown for P- and S-wave seismic imaging, also including results of combined application of both wave types.

Keywords: high-resolution seismic; electric vibroseis source; P- and S-wave recording; low harmonic distortion

1. Introduction

Using multiple linear synchronous motors (LSM) in instead of hydraulics in a vibroseis source is an innovative development in recent years, E-vibes. However, the concept was introduced years ago (Drijkoningen et al., 2006). The usage of LSM in a vibroseis creates a frictionless and contact free design. The frictionless and contact free design results in no wear, no viscous losses and no fluid leaks. Furthermore, there is no temperature dependency. Meaning that the repeatability is unprecedented. Moreover, the capability to produce linear forces at low frequencies and full force (100% drive level) enables to generated seismic signals with lower distortion compared to conventional vibroseis sources. Based on the E-vibe technology, a novel engineering fully electric vibroseis source, called the Lightning, capable of generating both P- and S-wave was developed and commercialized.

2. Lightning E-vibe technology and components

The Lightning E-vibe is a small and compact electric seismic sources using multiple linear synchronous motors (LSM) to generate acoustic signals for seismic acquisition in a frequency bandwidth of 3-400Hz. The system was originally build for tunnel boring machines (TBM). A TBM drills blindly into a tunnel, which can cause hazardous situations. To minimize these hazardous situations, multiple Lightning E-vibes were placed on the cutter head of the TBM to generate seismic data. By using full wave form inversion the required shear-wave velocity for subsurface imaging was estimated in an automatic way (Bharadwaj, 2017). In this way, a seismic image can be created of the subsurface in front of a TBM within one hour. Based on the successful results of the Lightning E-vibe in tunnel boring applications, the system was further developed for other engineering purposes.

The electric vibroseis consists of a baseplate and a reaction mass. The baseplate weighs 40kg and since the system is both a P- and S-wave source, the whole cover of the electric vibroseis source is part of the baseplate concept. The reaction mass weighs 40kg and is guided by a leaf spring design. The linear synchronous motors consist of two parts. One part are the coils, which are attached to the base plate assembly. The other part are the magnet racks, which are attached to the reaction mass assembly. The two motors combined produce a force of 1700N in S-wave and 1200N in P-wave. The useable frequency bandwidth is 3-400Hz. To measure the weighted sum ground force (Sallas, 1984), two accelerometers have been used. One on the baseplate and one on the reaction mass to estimate ground force measuring accelerations on the base plate and reaction mass. The size of the source is 520x490x210mm.

Figure 1. Lightning E-vibe shown in S mode

Figure 2. Lightning E-vibe shown in P mode

To provide hold down mass the Lightning E-vibe can be attached to a lifting system. The lifting system is, generally, attached to an electric vehicle but can be attached to any kind of vehicle with a tow hitch. The lifting system and carrier result in productive tool and improve the ground coupling. Most often the electric vibroseis is powered by a 45ah 48 VDC lithium ion battery and can also be powered by four 12V lead acid batteries.

Figure 3. Lightning E-vibe connected to lifting system and electric vehicle

3. Data examples

3.1. Source sweep signatures

Exact knowledge of the outgoing sweep signature is critical for the effective vibroseis correlation. In many cases the theoretical sweep signature (Pilot trace) is used for cross correlating with the recorded seismic traces. However the actual outgoing sweep signal is a combination of the signature measured on the Reaction Mass and the Base Plate of the vibroseis source. In case of the Lightning source high accuracy accelerometers are used for monitoring the Reaction Mass and Base Plate signatures. Recording these signals as auxiliary seismic traces enables calculation of the actual sweep signal for vibroseis crosscorrelation. Figure 4 shows recorded Pilot trace, Reaction Mass and Base Plate signatures for part of a seismic survey. As sweep parameters were unchanged for the recorded traces the Pilot trace, as a theoretical source signal is identical for each sweep. Reaction Mass and Base Plate signatures are measured signals, therefore vary from sweep to sweep. Lower part of Figure 4 shows the recorded auxiliary traces for 21 consecutive sweeps, while the upper part of the Figure 4 shows the zoomed 1.8 seconds of the traces. Please note, that the actual sweep start was at 1000 ms, therefore the upper plot starts at this start time. In the lower part of the figure aliasing of the image for the 20 seconds long sweep is evident, however trace to trace variations can be well estimated from the images. Both images in Figure 4 are plotted without individual trace scaling applied, therefore not only the stability of the signal shape, but its amplitude is also well visible. Some degree of sweep to sweep variation can observed in case of the recorded Base Plate signatures. This is expected, as the response of the Base Plate strongly depends on the coupling between the vibroseis source and the ground. This coupling is different for each shot point location.

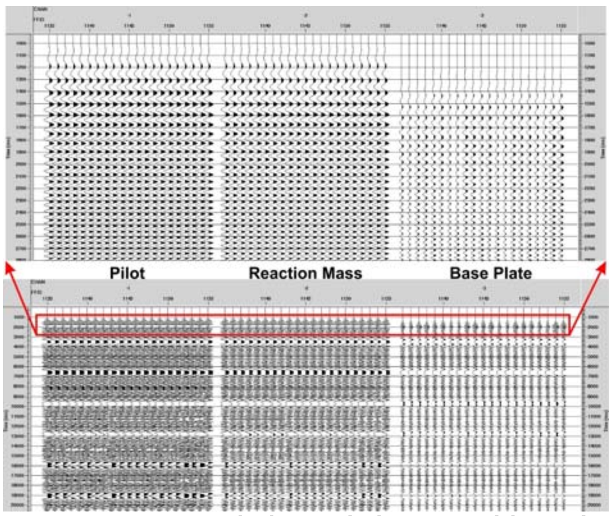

Figure 4. Monitoring the theoretical Pilot sweep, and the actual measured accelerations on the Reaction Mass and Base Plate of the vibroseis source. Lower part of the figure shows the signals recorded for a 20 seconds long sweep, while the upper part of the figure the first 1.8 s of the sweep zoomed.

3.2. Comparing P- and S-wave records

A 440 m long test profile was recorded along a flood protection dam in the Great Hungarian Plain. The profile was recorded with 4 m geophone spacing using 110 channels of 3C geophones as a fix spread shot with the Lightning vibroseis source both in P- and S-wave mode. For both P- and S-wave mode 20 seconds long sweep was used with 5-150 Hz linear up-sweep.

Subsurface geology below the dam consists of well layered sand-shale sequence deposited during Pliocene-Pleistocene. About halfway along the recorded profile a gas pipe was crossing below the dam. The gas pipe was laid in a ditch representing a disturbance zone below the dam.

Shot records with the same geophone spread location and source point for P- and S-waves are shown in Figures 5 and 6 respectively. For both figures shot gathers are shown with only trace equalization applied on the left and with Automatic Gain Control (AGC) and Band Pass Filtering (BPF) applied on the right panels. Maximum offset for both shot gathers is close to 400 m on the right hand side of the spread. Vertical scale in case of the P- and the S-wave gather is in Two Way Travel time (TWT), records are displayed between 0 and 2000 ms.

Note the very different characteristics of the two shot gathers. While in the P-wave record reflections are visible between the first arrival and the ground roll, in the S-wave shot gather bulk of the reflection energy is inside the ground roll. In the S-wave shot gather a distinct reflection arrival is visible as shallow as 250 ms.

First break arrivals can be used for refraction analysis or tomographic inversion in case of both P- and S- waves. For P-wave data one layer, the refraction from the water table is visible, while the S-wave record shows at least 3 break points in the first break arrival indicating 4 layers with distinctly different S-wave velocities.

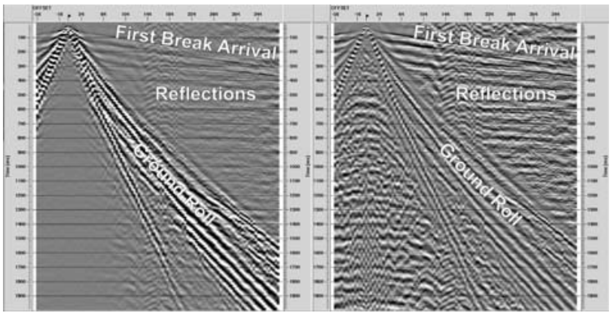

Figure 5. Shot gather with P-wave vibroseis source and 110 channel recording. Left panel is displayed with only trace equalization, right panel with AGC and BPF applied.

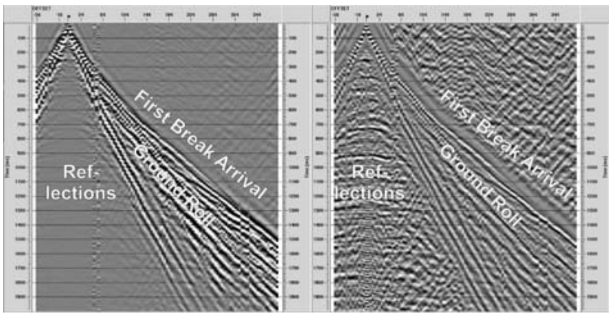

Figure 6. Shot gather with S-wave vibroseis source and 110 channel recording. Left panel is displayed with only trace equalization, right panel with AGC and BPF applied.

Both P- and S-wave reflection seismic profiles were processed and depth converted with the wave propagation velocities calculated during processing and the two depth converted seismic stack profiles are shown in Figure 7.

There are at least three striking differences between the P-and S-wave seismic profiles:

- In spite of the same sweep frequency used, the S-wave profile is of significantly higher resolution.
- Shallow imaging of the S-wave profile is clearly superior. Reflections are visible as shallow as 20 m, while for the P-wave profile the first reflection is below 100 m depth.
- Disturbance caused by the gas pipeline buried under the dam in a ditch is only visible in the S-wave reflection profile in the middle of the section.

For both the P- and the S-wave reflection profiles however we can state, that over 300 m penetration could be achieved with very good signal to noise ratio and excellent imaging of the subsurface layers. This result is a combination of the high quality source and recording system and also the well layered subsurface geology with gradually increasing seismic velocities with depth.

3.3. S-wave survey over a highly reflective subsurface

In a mountainous part of Hungary very different geological conditions were encountered during an S-wave seismic survey. The subsurface was characterized by a very “hard”, highly reflective shallow interface between Quaternary sediments and Permian rocks underneath.

A similar seismic survey was performed with 4 m geophone spacing, 3C single geophones used for sensing and 200 traces recorded in a split-spread geometry. Lightning vibroseis source was applied with 20 seconds sweep length and 5-100 Hz linear up-sweep.

Typical shot gather is shown in Figure 8 with AGC applied.

Most prominent difference is the well-defined first break arrival at early times compared to the ground roll from relatively small (50-60 m) to the maximum offsets on the record. The very near offset traces show S-wave seismic velocities around 260 m/s, followed by a second layer with approximately 340 m/s velocity. These are the typical velocity ranges for the Quaternary sediments in the top 20-30 metres. Below the Quaternary layers an abrupt change of S-wave velocity occurs, and for the rest of the recorded offset range a third layer with over 2000 m/s S-wave velocity is visible. This refraction interface was identified as the Permian claystone layer with typical depth of 20-30 along the measured profile.

In addition to the well-defined high velocity refraction event generated on the large offset traces, for the smallest offsets traces recorded the top Permian layer boundary also creates an S-wave seismic reflection event. This provides a unique opportunity to image the layer boundary and its depth variations as a seismic reflection event too.

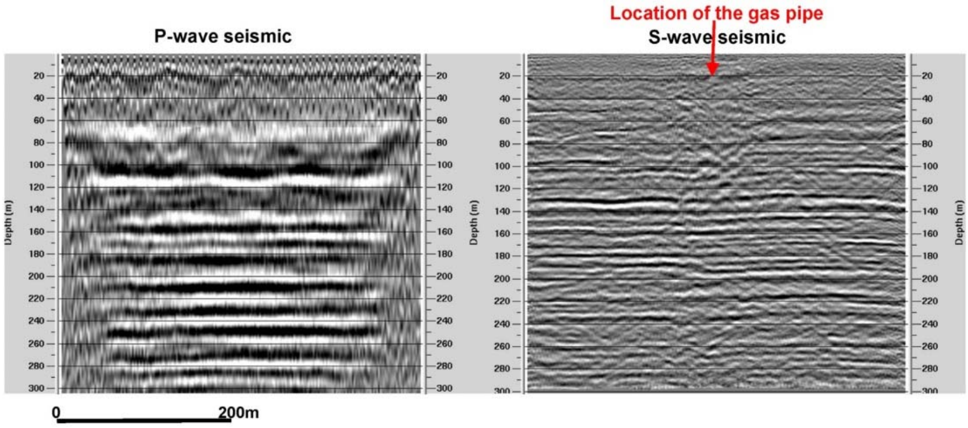

Figure 7. P-and S-wave reflection seismic profile measure along the same 400 m long section of the flood protection dam.

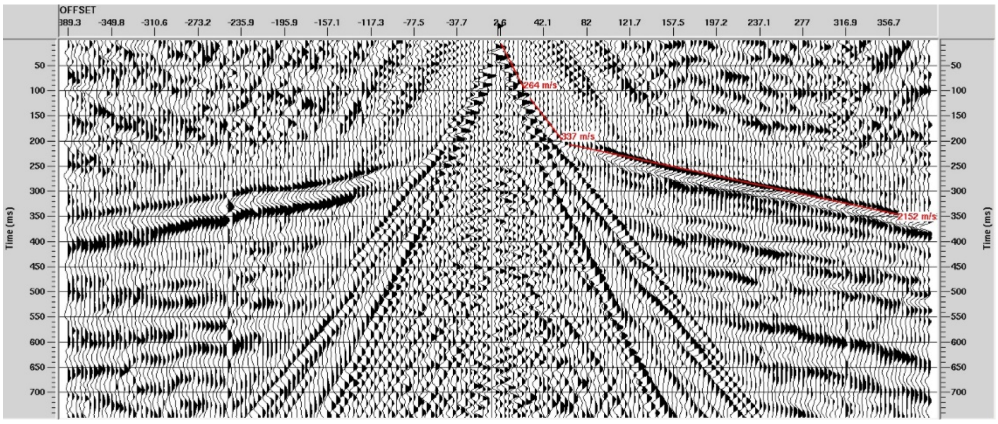

Figure 8. S-wave seismic shot gather recorded over a highly reflective shallow surface. Please note the very sharp change in S-wave seismic velocity and the imaging of the shallow reflecting interface.

4. Conclusions

The examples shown in this paper presented two end members of subsurface geology. The first example presented seismic records over a well layered, gradually increasing velocity subsurface, which is ideal for seismic imaging. The corresponding shot gathers and stack profiles showed high quality image of the subsurface down to several hundreds of meters.

In the second case a highly reflecting layer was present at a shallow depth. High resolution S-wave seismic recording could provide valuable information not only for the subsurface velocities, but also imaged the layer boundary as a reflecting surface. This was not possible before during previous high resolution P wave seismic surveys.

The E-vibe technology is currently further developed for much larger forces and deep resource targets as well as Co2 storage and EOR purposes. Moreover, the E-Vibe technology enables very accurate and precise synchronization of multiple sources. Many Lightning electric seismic sources can be synchronized with an accuracy of 10 microseconds. This will provide a seismic source with wide frequency bandwidth, low distortion and higher energy.

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