SUMMARY

In this paper we present a newly developed vertical seismic vibrator driven by linear motors. We explain the different components the vibrator consists of. We show that the harmonic distortion of the linear-motor vibrator signal is very small. We also show that, without applying a feedback loop on the pilot signal, the weighted-sum ground force signal and its harmonics, is heavily depended on the coupling of the vibrator with the ground.
Introduction

Recently, the idea of using linear motors for generating seismic signals has been introduced (Drijkoningen et al., 2006). The biggest advantage of using linear motors is the fact that they can produce linear forces at low frequencies, resulting in lower distortion of the signal compared to for example hydraulic or electromagnetic shakers. Delft University of Technology, together with the companies MI –Partners and Magnetic Innovations, has designed and built a vertical vibrator based on Linear Synchronous Motor (LSM) technology. The aim is to use it for monitoring which can be done with smaller systems than conventionally used in hydrocarbon exploration. Still, it can be used for exploration of shallower targets too. The vibrator is shown in figure 1. In this abstract the setup and characteristics of such a linear-motor shaker and some preliminary data will be presented.

Vibrator components

Since the vibrator is relative small compared to exploration-type vibrators, the design of the system was to use only a reaction mass and no hold-down mass. Therefore the vibrator can be seen as two masses that move relative to each other to produce the seismic waves wanted, figure 2. In our case, the base-plate has a weight of about 200kg and the reaction mass has a weight of about 1000kg. The driving force, in contrast to hydraulic vibrators, is produced by linear motors. Each linear motor consists of a permanent magnet track fixed on the reaction mass and a coil track fixed to the base-plate. In total six synchronised linear motors are used in a triangular set-up. The system has been designed (Jenneskens et al., 2011) to deliver a ground force of about 6.5kN in a frequency bandwidth from 2 and 200Hz. Lower frequencies, with smaller force, and higher frequencies, with more distortion, are possible as well. The individual motors, after being correctly calibrated, are placed such that the sum of their moment of force is minimal to prevent horizontal movements of the reaction mass. Leaf springs have been added to provide a frictionless guiding for the reaction mass in the vertical direction. To lower the power consumption the linear motor is not used to lift the reaction mass to its initial position, instead an air spring is used as gravity compensator. The air spring does add a resonance frequency around 1 Hz to the system, for which the driving amplitude has to be modified. The shaker design was optimised with the help of a finite element model that predicts the response of different configurations. In operation the tilt and relative position of the reaction mass as well as the accelerations of both the masses are recorded and can be used for control loops. Our
vibrator contains four accelerometers, one on the base-plate and three on the reaction mass, which are both used to calibrate the individual motors as to measure the vertical force produced using the weighted-sum approach as for example described by Castanet et al., (1965) and Sallas (1984).

**Harmonic distortion**

Since low harmonic distortion should be a characteristic of a linear-motor system, we measured the separate signals from the vibrator in the field with the aim to quantify the harmonic distortion. To that aim, the LSM vibrator was driven with a linear 30 seconds sweep from 2 to 200Hz. Drive level was set to about 50% and no feedback loop was applied to the pilot signal. Figure 3 shows the time-frequency plot of the pilot, weighted-sum ground force, reaction mass and base-plate acceleration.

**Figure 2** A 2D model of the vertical seismic linear-motor shaker, showing the base-plate (grey), reaction mass (black), permanent magnets (green), driving coils (orange), leaf springs (red) and the air spring used to compensate for gravity (blue).

**Figure 3** Time-frequency contour plots made with a normalised Gabor transform, showing the pilot signal (a), weighted-sum ground force (b), reaction mass (c) and base-plate acceleration (d). Amplitude scale is given in dB relative to the maximum amplitude of each of the signals.
From figure 3 it is clear that the vibrator creates very little harmonic distortion. The overtones are 30 dB smaller than the fundamental signal, figure 3(b). The harmonics in the weighted-sum ground force signal are mainly due to the base-plate signal, figure 3(d), while the reaction mass signal, figure 3(c), has very little harmonic distortion.

**Coupling effects on harmonic distortion**

The harmonic distortion depends on the coupling of the vibrator to the ground. To investigate these effects four different rubber mats were placed between the base-plate and the ground. The vibrator was again driven by a 30 seconds sweep from 2 to 200Hz and no feedback was applied to the pilot signal. Figure 4 shows the time-frequency plot of the weighted-sum ground force for the different mats used; bubble Sof-Tred (A), polyurethane foam (B), neoprene open cell rubber (C) and solid rubber (D). Figure 5 shows the spectra of the weighted-sum ground force, reaction mass acceleration and base-plate acceleration for the four different coupling conditions.

![Figure 4](image-url)

**Figure 4** Time-frequency contour plots of the weighted-sum ground force for different coupling cases. Mats of the following material were placed between the ground and the vibrator; bubble Sof-Tred (A), polyurethane foam (B), neoprene open cell rubber (C) and solid rubber (D). Amplitude scale is given in dB relative to the maximum amplitude of each of the signals.

The generation of harmonics strongly changes depending on coupling condition, as visible in figure 4. For the open cell materials (B and C) the second harmonic is more pronounced, up to -25 dB relative to the fundamental signal, compared to the closed cell/solid mats (A and D), were it reaches -35dB at most. The coupling influences the different harmonics independently, visible in the results using the polyurethane foam mat (B). The second harmonic is relative strong (about -25dB), but the third harmonic (about -35dB) is relative weak. Apart from the harmonics, the amplitude of the signals changes a lot for the different situations. The amplitude difference of the weighted-sum ground force reaches up to about 7dB for the different mats, figure 5(a). As expected the difference is mainly due to the base-plate signal, figure 5(c). The reaction mass, figure 5(b), behaves almost the same in all four situations.
Conclusions

We have successfully designed, modelled and built a linear-motor seismic vibrator. The first preliminary data shows that the vibrator produces very limited amount of harmonic distortion. The distortion of the ground force signal is mainly due to the base-plate signal and depends strongly on the ground coupling of the vibrator.

Acknowledgements

This work has been sponsored by the Research School of Integrated Earth Sciences (ISES). It is also supported by the Nederlandsche Aardolie Maatschappij (NAM). Alber Hemstede is very thanked for his technical support.

References

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