A 10 kN portable electromagnetic vibrator for near-surface studies

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SUMMARY

In a previous paper, we described how a small electromagnetic vibrator could be manufactured using commercially available components for less than US$2,000. The basis of the unit was a set of four low-frequency actuators designed for use in home-theatre systems. In this paper we describe a new unit with the number of actuators increased from four to ten and improved quality electronic components.

The maximum output of the vibrator, as measured using load-cells, was more than 10 kN; when operating the unit in the field we noticed that the weight of the vehicle was not sufficient to prevent it decoupling. Variation between the load-cell and accelerometer measurements, consistent with similar studies conducted using hydraulic vibrators, suggests that the new unit has considerable potential as a research tool looking at issues such as baseplate flexure. A VSP acquired using distributed acoustic sensing showed a signal to a depth of 850 m for a single sweep.

Key words: near-surface, land seismic, Vibroseis

INTRODUCTION

In a previous paper (Dean et al., 2018), we described how a small electromagnetic vibrator could be manufactured using commercially available components for less than US$2,000. The basis of the unit was a set of four low-frequency actuators designed for use in home-theatre systems. The final point we made in our discussion was that “the energy could easily be increased by adding more actuators”. In this paper, we describe the construction and performance of such a unit.

DESIGN

As with our previous unit the new vibrator was constructed from commercially available components (Table 1) but differed in several ways. Originally, we used the output from the computer’s built-in sound card to play the sweeps but we found that the output from sound cards varied (Figure 5 in Dean, Nguyen, Kepic and Halliday (2018)) thus the output force of the vibrator would vary depending on the computer it was connected to. To overcome this issue we decided to test some external sound cards. We selected the ASUS Xonar U7 kn2 and SoundBlaster model 581560 and compared their output levels for mono-frequency signals between 15 and 180 Hz using an oscilloscope. The noise levels were consistent, but the output of the SoundBlaster was more than twice that of the Xonar and the computers built-in sound card. We therefore selected the SoundBlaster for use in our new system.

Table 1. A list of the components used to construct the portable vibrator and their unit and total cost.

<table>
<thead>
<tr>
<th>Description</th>
<th>Model Used</th>
<th>No. of units</th>
<th>Cost/Unit (US$)</th>
<th>Total Cost (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuators</td>
<td>Buttkicker LFE</td>
<td>10</td>
<td>340</td>
<td>3,400</td>
</tr>
<tr>
<td>Amplifiers</td>
<td>Alpine PDX- M12</td>
<td>5</td>
<td>760</td>
<td>3,800</td>
</tr>
<tr>
<td>Line driver</td>
<td>Rockford Fosgate RFPEQU</td>
<td>1</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Sound card</td>
<td>SoundBlaster model 581560</td>
<td>1</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Batteries</td>
<td>Ultimate UL-120-V031</td>
<td>4</td>
<td>350</td>
<td>1,400</td>
</tr>
<tr>
<td>Ramps</td>
<td>Stanfred 4WD</td>
<td>2</td>
<td>110</td>
<td>220</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>9,010</strong></td>
</tr>
</tbody>
</table>

As for our previous design we initially connected the output of the sound card to a car stereo but we found that the output of the stereo was heavily distorted, particularly when the volume was set high enough to get the optimum 8 volt input for the amplifiers. At the suggestion of a local car audio shop we replaced the stereo and pre-amplifier with a line driver (Rockford Fosgate RFPEQU). By tuning the line-driver to the output of the sound card we could limit the maximum output of the line driver to 8 V. Figure 1a shows how the RMS output of the line driver varies at different frequencies, varying by less than 0.5 V between 15 and 180 Hz. The reader is cautioned that any ‘Bass Boost’ functionality should be disabled; Figure 1b shows the output when Bass Boost is active, resulting in the output more than doubling at frequencies centred on 45 Hz.

![Figure 1. (a) RMS output of the line-driver as measured for different mono-frequency signals. (b) RMS output of the line-driver as measured for different mono-frequency signals when the ‘Bass Boost function’ is operational.](image-url)

The waveforms output by the line driver were also recorded using an oscilloscope. Example output waveforms at 10, 100,
10 kN portable electromagnetic vibrator

and 180 Hz are shown in Figure 2. At all frequencies the noise level is at least 50 dB down with no evidence of harmonic contamination.

Figure 2. Examples of the waveforms output by the line driver at three different frequencies. Note that the time scales have been varied for the three frequencies shown and the PSD results normalised.

The amplifiers we used previously were no longer available, so we took the opportunity to replace them with a set of five Alpine PDX-M12 amplifiers. These amplifiers are capable of supplying 1200 W RMS into 4 Ω and each amplifier was connected to a pair of actuators in parallel (the impedance of each actuator is 4 Ω). Most importantly, the frequency response of these amplifiers is flat between 5 and 400 Hz (cheaper amplifiers typically have a flat response limited to ~20 Hz).

The previous version utilised only four transducers but still required a person sitting on the unit to prevent it from decoupling. The output for the new version is much higher so to be able to provide sufficient hold-down we mounted the actuators onto a 0.75 x 0.35 m 12 mm thick Aluminium plate which was in-turn covered by a car ramp (Figure 3). The idea being that a car could be driven onto the ramps to provide hold-down with the cars suspension acting to insulate the car from the vibrations (Figure 4).

Figure 3. Photograph showing the ten actuators mounted on the plate with the car ramp.

Figure 4. Photographs showing a vehicle providing the hold-down to the vibrator.

PERFORMANCE

The output of the vibrator is restricted by three different attributes:

- Mass displacement – as with hydraulic vibrators, if the mass inside the actuators moves too far from its central position it will knock on the top/bottom of the case (‘slamming the mass’).
- Current – The current drawn by the system should not exceed 100 A, the safe current draw of the batteries and the rating of the switch and fuse.
- Volume – The output of the sound card could not be increased further.

Figure 5 shows the results of a series of testing using mono-frequency signals. At frequencies less than 15 Hz the vibrator is displacement limited and the volume had to be reduced to 24% to avoid slamming the mass. Between 15 and 130 Hz, the volume had to be reduced to avoid exceeding the 100 A current limit. Above 130 Hz the output of the vibrator is limited by the volume output of the sound card. As the frequency increases above this limit the current, and therefore the likely output of the vibrator, decreases.

Figure 5. Graph of the volume setting and resulting current draw for different mono-frequency signals. The magenta, cyan and green boxes indicate frequencies where the output is limited by the displacement, current and volume respectively.
SWEEP DESIGN

As for our previous unit the sweep was generated using an iterative process. Specifically, the volume of the sound card was set to 100% and then, starting at the low frequencies, and with a very limited bandwidth, the amplitude of each frequency within the sweep was adjusted so that the displacement and current limits (100 A) were not exceeded. Once the output of the sweep was maximised within these limits the sweep bandwidth was then increased by another 10 Hz and the process repeated until the performance of the vibrator across the full bandwidth (10 to 180 Hz) had been characterized. As with our previous unit, the maximum volume at each frequency for a sweep was lower than the mono-frequency results (Figure 5) suggested.

The process described in Bagaini et al. (2008) and Dean et al. (2016) was then used to generate a sweep with a flat power spectral density across all frequencies. The reduction in volume at low frequencies results in the time spent at these frequencies to be significant, the first 10 s of the 30 s sweep being spent between 10 and 17 Hz. Obviously, the time cost involved in obtaining this low frequency energy is considerable, but for the purposes of further testing a 10 to 180 Hz sweep was employed.

LABORATORY TESTS

The performance of the vibrator was tested in the laboratory using a combination of accelerometers and load cells. Data was recorded using an eight channel ‘Sandwich Box’. We placed three accelerometers at the edges of the plate and three 200 kg load cells (Phidgets 3137) beneath the plate (we experimented using four load cells but the plate was unbalanced) as shown in Figure 6. We used the remaining two channels to record the signals from a coil placed at the end of the plate and the pilot. Hold down was provided during the testing by two PhD students standing on the vibrator.

Figure 6. Diagram of the laboratory setup used to test the vibrator. A1-A3 are the three accelerometers, LC1 to LC3 the three load cells. The actuators are shown in blue and the plate in green.

Frequency-time plots of the traces recorded while transmitting the sweep at a volume of 50% are shown in Figure 7. The load cell traces (Figure 7f to h) are noisier than the accelerometer traces (Figure 7c to e), the noise floor is about -50 dB and some electrical noise is evident at 50 Hz, but they do not show any evidence of harmonics, unlike the accelerometer and coil traces that suggest significant harmonics being generated.

Figure 7. Frequency time plots of the pilot, coil, accelerometer (AC), and load cell (LC) traces with the sweep transmitted at 50% volume to avoid decoupling. All the plots have been normalised and have a dynamic range of 80 dB.

Figure 8 shows the frequency-time plot and power spectral density plots for the summed load-cell traces for the sweep when transmitted at 30% and 70%. The second harmonic is visible on the 80% volume data (Figure 8b) and at the lowest frequencies is only ~15 dB down from the fundamental. Although the strength of the fundamental increases over the duration of the sweep, the strength of the 2nd harmonic does not. In the later part of the sweep (>23 s, >50 Hz) additional harmonics become visible but they are at least 40 dB down from the fundamental. For the 30% volume sweep (Figure 8a) it is not possible to identify any harmonics, likely due to the noise level. The PSD plots (Figure 8c and d) show that the low frequency output of the vibrator falls below that of the pilot but that the vibrator is very efficient at transmitting high frequencies.
**FIELD TESTS**

To test the vibrator in the field we recorded downhole data using a Distributed Acoustic Sensing (DAS) system. The fibre interrogated is permanently cemented in a 900 m deep borehole located on the Curtin University campus (Correa et al., 2017). Gauge length was 10 m and spatial sampling interval 1 m. The source was positioned at an offset of 50 m and the sweep employed was that shown in Figure 7a.

Figure 9 (left panel) shows the shot record obtained using a single sweep of the vibrator. To compare with a more conventional source, data was also recorded using a Buffalo gun (Pullan and MacAulay 1987) and this is shown in the right panel of Figure 9. The SNR of the Vibroseis data is superior with the first break clearly visible to the bottom of the record, there are also several reflections evident on the Vibroseis data that do not appear on the Buffalo gun data. The frequency-time plot of the Vibroseis data (not shown) shows little evidence of harmonic contamination, although the noise level is quite high and the gauge length response (Dean et al. 2016) reduced the high frequency content significantly.

**DISCUSSION AND CONCLUSIONS**

In our previous work (Dean et al., 2018), we showed how a simple electromagnetic Vibroseis source could be constructed from commercially available components. In this paper we created a new vibrator with the number of actuators increased from four to ten. The output from the vibrator was increased, not only from the extra actuators but also by improving the output and quality of the electronic components, particularly the use of amplifiers with a better low frequency output.

The maximum output of the vibrator, as measured using load-cells, was more than 10 kN; when operating the unit in the field we noticed that the weight of the vehicle was not sufficient to prevent it decoupling. To make the unit more useful for field studies we need to develop an alternative to the car ramps currently employed that will enable more of the weight of the vehicle to be employed as hold-down. The variation between the load-cell and accelerometer measurements (Figure 7) is consistent with similar studies conducted using hydraulic vibrators (e.g. Dean et al., 2015) and suggests that the new unit has considerable potential as a research tool looking at issues such as baseplate flexure. The effectiveness of the vibrator can be seen by the VSP data quality shown in Figure 9, signal is visible to the full depth of 850 m even for a single sweep.
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REFERENCES


