Design and Application of an Electromagnetic Vibrator Seismic Source

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ABSTRACT

Vibrational seismic sources frequently provide a higher-frequency seismic wavelet (and therefore better resolution) than other sources, and can provide a superior signal-to-noise ratio in many settings. However, they are often prohibitively expensive for lower-budget shallow surveys. In order to address this problem, I designed and built a simple but effective vibrator source for about one thousand dollars. The "EMvibe" is an inexpensive electromagnetic vibrator that can be built with easy-to-machine parts and off-the-shelf electronics. It can repeatably produce pulse and frequency-sweep signals in the range of 5 to 650 Hz, and provides sufficient energy for recording at offsets up to 20 m. Analysis of frequency spectra show that the EMvibe provides a broader frequency range than the sledgehammer at offsets up to ~10 m in data collected at a site with soft sediments in the upper several meters. The EMvibe offers a high-resolution alternative to the sledgehammer for shallow surveys. It is well-suited to teaching applications, and to surveys requiring a precisely-repeatable source signature.

Introduction

The choice of an appropriate seismic source is vital for any seismic survey, but budgetary constraints frequently limit one's options. For shallow surveys, a sledgehammer (*e.g.,* Keiswetter and Steeples, 1995) is often the preferred option. It is effective and economical, but the repeatability from one strike to the next can be far from perfect. And while stacking improves the signal-to-noise ratio, it degrades the resulting waveform because strike-to-strike variations lead to the partial cancellation of the higher frequencies. Moreover, successive hammer impacts deform the area of impact, precluding exact source repeatability and possibly damaging the subject of study (asphalt, etc.).

Vibrator sources (*e.g.,* Anstey, 1991) address many of these shortcomings, but are frequently too expensive to consider for shallow seismic surveys. The Industrial Vehicles Inc. (IVI) Minivib (*e.g.,* Narbutovskih *et al*., 1995; Miller *et al*., 1996; Doll *et al*., 1998) is considerably smaller than petroleum exploration vibrators, but is still too large and expensive to consider for most small-scale seismic surveys. Ghose *et al.* (1998) describe a portable vibrator system that is effective and transportable, but which does not meet the budgetary requirements of many academic studies. Similarly, the Earth Reaction Seismic Source (ERSS) by Elohi Geophysics Inc. (*e.g.,* Cadimona *et al*., 1996) is portable and effective, but out-of-reach for low-budget surveys. Soil compactors may be used in shallow seismic surveys, such as a Mini-Sosie source (*e.g.,* Sexton and Jones, 1986), but the required "pseudorandom" source sequence can be difficult to achieve without complicated (and expensive) electronics.

I have developed an inexpensive electromagnetic vibrator source, called the EMvibe, that can produce any desired seismic time series. Sweeps or pulses may be stacked cleanly, resulting in a high-frequency source wavelet. The EMvibe can be used without damaging the site, and with little or no permanent plastic deformation of the study area. It does not replace the sledgehammer or supersede pre-existing vibrator sources, but it offers an alternative that is simple, inexpensive, and well-suited to certain applications such as high-resolution reflection or the Continuous Surface Wave (CSW) method (*e.g.,* Matthews *et al*., 1996).

The EMvibe is a highly-repeatable seismic source that can be built for just over $1,000, a price that is within the bounds of most budgets. In order to create an effective and economical vibratory source in a timely manner, I utilized a combination of off-the-shelf electronics and simple-to-machine mechanical parts. Field data demonstrate the utility of the source, and allow comparison with sledgehammer stacking results.

Vibrator Design

The EMvibe consists of an electromagnetic transducer mounted in a rigid framework that transfers vibrations to the earth. The first two parts of this section describe these two principal parts of the EMvibe, and the third part describes the electronics used for signal generation and production.

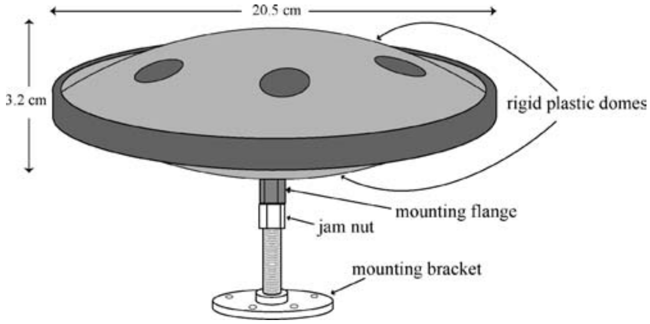

Figure 1. Diagram of transducer used in the EMvibe. A magnet and an electric coil are attached to the inside of the two plastic domes, such that a current in the coil causes relative motion between the domes (similar to a standard audio speaker).

Transducer

The heart of the EMvibe is an off-the-shelf audio device produced by Clark Synthesis of Littleton, CO (www.clarksynthesis.com). It is termed a "tactile transducer" and is used to shake physical objects with a desired broadband, time-domain, signal. Vibration is produced by a coil of wire and a strong magnet, much like a standard audio speaker, but instead of a paper cone designed for the impedance of air, the device has two stiff plastic domes which are designed to match the impedance of solid objects. With the magnet attached inside one dome, and the coil attached inside the other, the tactile transducer vibrates when an alternating current is applied. Because the magnet is sufficiently strong and massive, the device vibrates objects to which it is bolted. It is designed for use in home theater seating, theme park rides, and military vehicle simulators, and it offers the power necessary to produce a vibratory signal in the earth.

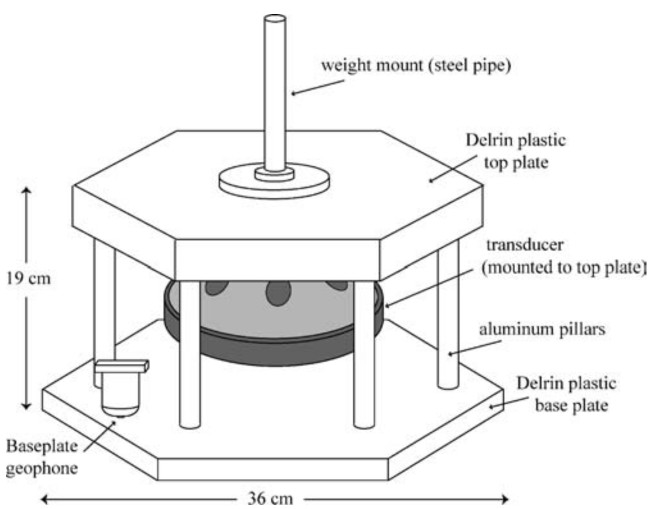

Figure 2. Sketch of vibrator framework, with essential structural parts labeled. The transducer vibrations are conducted to the earth by the rigid assembly.

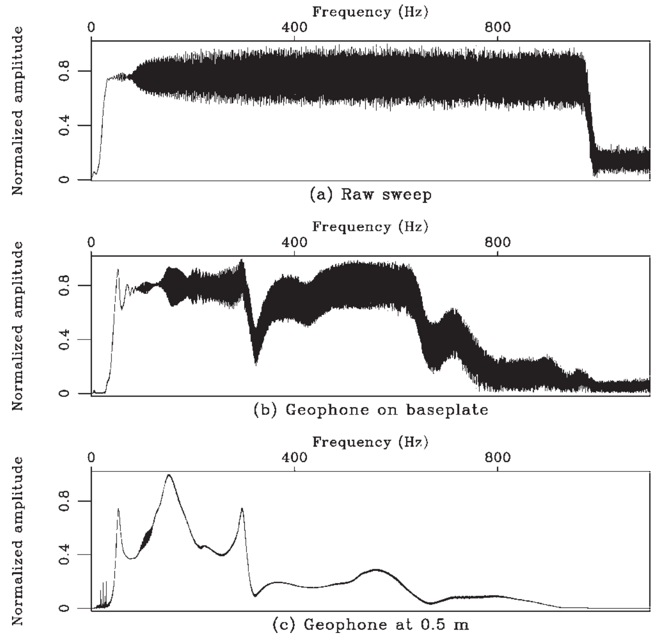

Figure 3. Comparison of normalized frequency spectra for a) the raw sweep, b) vertical base plate velocity, as measured by the 40-Hz vertical geophone on the plate, and c) vertical particle velocity at 0.5 m, as recorded by a geophone at that position.

The Clark Synthesis model TST-429 tactile transducer employs a 567 g (20 oz) neodymium magnet, and offers an even frequency response over the range 5 to 800 Hz according to the product specifications, although a response curve is not provided. It is designed to be powered at a continuous level of 135 watts, and a peak power of 400 W. The device measures 20.5 cm in diameter, and is 3.2 cm thick (see Fig. 1). It is mounted to objects by way of the mounting flange which is affixed to one of the domes. Because the flange is part of the dome that is attached to the coil, the 567 g magnet on the opposite dome acts as the reaction mass for the vibrator device. Although this is not a very large mass relative to other seismic vibrators, I find it to be adequate for producing a seismic signal measurable at 10 or 20 m offset.

Framework

Figure 2 shows the framework which houses the tactile transducer and conducts its vibrations to the soil. It is a rigid structure of machined aluminum and Delrin plastic (made from an acetal homopolymer resin produced by DuPont). These materials are both very rigid, and they can be readily obtained and are easy to work with. Starting with raw stock and very minimal machine shop experience, I produced the needed parts with about a half-week of work. The transducer is designed to be hung beneath its mounting surface, so it is

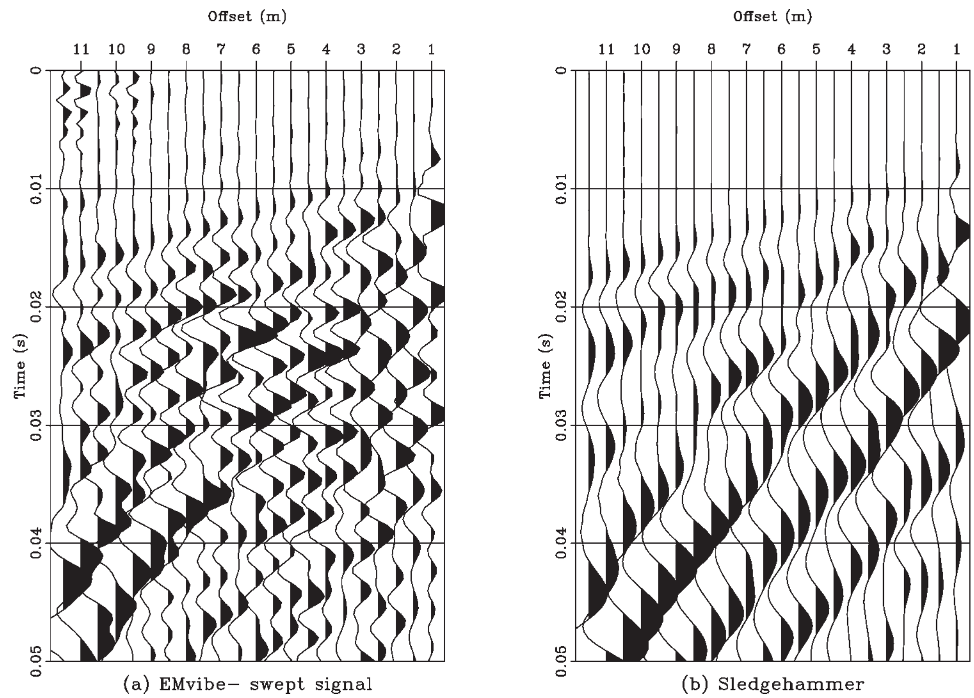

Figure 4. Comparison between a) EMvibe results from stacking ten 30-second sweeps (5 to 650 Hz) and b) stacking ten hammer strikes. Data were recorded with 40-Hz vertical geophones spaced at half-meter intervals. Data are displayed with a 100 to 600 Hz bandpass filter, and automatic gain control (centered 75-sample window).

attached to the 4.6 cm-thick Delrin top plate as shown in Fig. 2. The top plate is supported by six 2.3 cm-diameter, 13 cm-long, aluminum posts. These posts transfer the energy to the 2.3 cm-thick Delrin base plate, which is resting on the soil. The parts are bolted together with standard 6.3 cm-long steel bolts which pass through the top and base plates and thread into the ends of the aluminum posts. A magnetically-shielded vertical 40-Hz geophone on the baseplate provides data on the actual vibrator motion.

In order to improve coupling, six 7.5 cm spikes (removed from unwanted geophones) extend from the bottom of the baseplate. These spikes are easily removed for vibrator use on rock or other hard surfaces. In addition, a 2.5 cm-diameter pipe extends upward from a flange on the top plate, allowing weights to be stacked on top of the EMvibe. I use buckets of cement, with holes in the center to permit the weight support pipe to pass through, though any weight that fits snuggly over the pipe is equally functional.

Signal Generation and Amplification

I create the source signal (described in the next section) on a field laptop computer, and output it via a Sonica (brand) M-audio 24-bit USB sound device (www.m-audio.com), though any higher-quality sound device would suffice. The device produces a high-quality but low-power signal which passes through a small pre-amplifier and then to a 450 watt-per-channel rack-mount two-channel power amplifier, intended for musical performances. The amplifier is designed for transportable durability, and so is well suited to field use. It offers high power and good signal quality, but requires 120-volt AC power. Car stereo amplifiers offer a 12-volt battery alternative, but large amplifiers require enough power that auxiliary AC power would be required to keep the battery charged during a day of use. Though a limitation, the need for AC power can be easily accommodated with a generator or extension cords at most field sites.

Field Data Comparison

I employ two different types of source waveform with the EMvibe. Because vibratory sources permit the use of long time series, it is common and sensible to use frequency sweeps (Anstey, 1991). Frequency sweeps (and other input time series) offer signal-to-noise improvements proportional to $T^{1/2}$, where T is the duration of the time series. Because small vibratory sources also offer near-perfect repeatability (the small-magnitude vibrations do not deform the local soil properties, and the device can reliably produce the same exact signal again and again), the use of stacked pulse signals is also an effective option. In this case, the signal-to-noise ratio improves as $N^{1/2}$, where N is the number of stacked pulses. While each pulse is not very strong, N can be very large with minimal effort. In this section I present

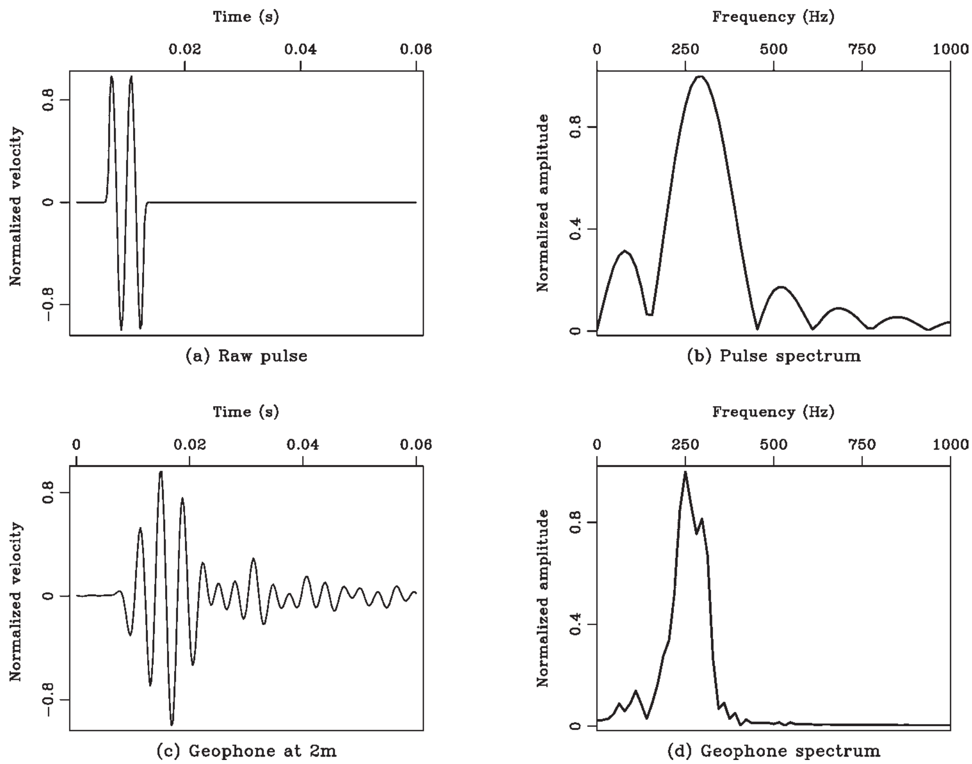

Figure 5. a) Raw pulse used for data shown in Fig. 6a (2 cycles of a 300 Hz sine wave, tapered at the ends). b) Spectrum of the raw pulse. c) Data from vertical geophone at 2 m, result of stacking 100 pulses. d) Frequency spectrum of 0.0 to 0.04 s portion of trace shown in part c). Note that higher frequency portion of the original pulse has been lost, but that the main lobe remains.

a comparison between results from sweeps and pulses and sledgehammer stacking.

Linear Sweep Signals

The linear sweep is the simplest vibrator sweep and is generally quite effective. A linear sweep from frequency f_{min} to f_{max} is easily produced with the simple algorithm

$$f(t) = f_{min} + \frac{(f_{max} - f_{min})t}{2} \tag{1}$$

where *f*(*t*) is frequency as a function of time *t*. The primary disadvantage of the linear sweep is that it does not take into account the vibrator or earth responses, and so it may result in an uneven spectrum and survey inefficiency (Pritchett, 1994). I record data with a 24-channel Geometrics Geode seismograph offering 64,000 samples per record, and so can record for as long as 32 s with a 0.5 ms sample interval and can therefore use up to a 30-second sweep. Because the device is intended for academic rather than exploration use, the slight inefficiency of the long linear sweep (the long sweep leads to slower data collection) does not present a major problem and I can simply stack more sweeps to enhance any weaker frequencies. After testing various sweeps, I find that 30-second sweeps from 50 to 650 Hz, with a half-second taper at each end, are quite effective.

Figure 3a shows the frequency spectrum of a raw sweep (1 to 1,000 Hz), essentially flat from about 25 to 975 Hz (the half-second taper at each end of the sweep accounts for the bulk of the "missing" 25 Hz at each end of the sweep). The actual frequency spectrum of the resulting vibrations (as recorded by the geophone on the baseplate) is shown in Fig. 3b. This is the frequency response of the EMvibe, and shows a fairly flat response from 50 to 625 Hz, with the exception of the obvious notch at 325 Hz. Another notch at 675 Hz is within the down-slope of the frequency response and marks the high end of the useful frequencies. A geophone located ~0.5 m from the EMvibe (Fig. 3c) shows that the higher frequencies do not efficiently couple into the earth and/or that they attenuate quickly. Figure 3 clearly shows that the EMvibe is most effective in the range 50 to 650 Hz so I employ that frequency band for field surveys, with the knowledge that the frequency response is non-linear.

Vibrator data resulting from sweeps must be cross-correlated with a pilot trace to compress the source time series to (ideally) a spike before the data can be interpreted. Comparison of correlation results using, respectively, the raw sweep, the baseplate motion data, and data from the geophone at 0.5 m, as the pilot trace show that the original sweep produces gathers that are the clearest and least reverberatory. Data are correlated using the raw sweep, and then

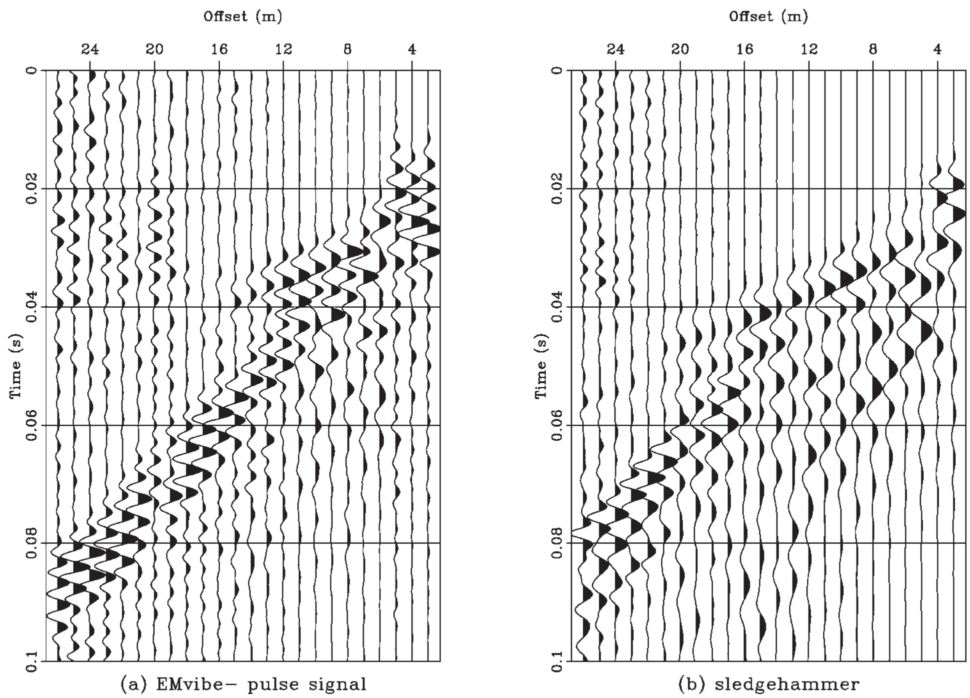

Figure 6. Comparison between a) EMvibe results from stacking 900 pulses (described in the text) and b) stacking five hammer strikes. Data were recorded with 40-Hz vertical geophones spaced at 1-m intervals. Display filter: 140 to 650 Hz bandpass filter.

stacked to produce each shot gather. Slight triggering variations are addressed with an auto-shift algorithm that uses cross-correlation to calculate shifts that are applied to each gather before stacking.

Figure 4a shows a gather created by stacking ten vibrator sweeps (5 to 650 Hz), and Fig. 4b shows data collected by the same geophone array but with ten sledgehammer impacts as the source. Both are displayed after application of a minimum-phase 100 to 600 Hz bandpass filter, and automatic gain control (AGC) using a centered window of length 75 ms. The data were recorded by a 24-channel seismograph deployed with 40-Hz vertical geophones at half-meter intervals and the source 1 m from one end of the geophone line. The site is located in Redwood City, California, on a small beach area adjacent to the San Francisco Bay. The subsurface geology consists of layers of sand, clay, and sea shell shoals. The data plots in Fig. 4a and b show similar features, including ground roll and a refracted first arrival. The vibrator data show more high-frequency energy than the hammer data, and shows the first breaks more clearly as well. The sledgehammer data show more low-frequency groundroll energy. No clear reflections are visible in the data, nor have any been observed in other seismic data collected at this site.

Pulse Signals

Short seismic pulses exploit the repeatability of the EMvibe and do not require long record lengths or correlation with a pilot trace. They can include any frequencies desired, and many copies can be stacked with little effort. Pulses are made up of a small number (one, two, five, etc.) of cycles of a sine wave of a given frequency (in this case, between 100 and 800 Hz). After testing various numbers of cycles of various frequencies, a pulse composed of two cycles of a 300 Hz sine wave was deemed to be the best option for the EMvibe in the chosen test setting. Figure 5a shows this pulse, with the frequency spectrum in Fig. 5b. The ends of the pulse are tapered with an exponential function to avoid a sharp-onset signal going to the amplifier and vibrator.

The gather shown in Fig. 6a is a stack of 900 individual pulses (2 cycles of a 300 Hz sine wave) as recorded by 40-Hz vertical geophones at 1-m spacing. The source was 3 m from the nearest phone, and the site is a grassy lawn on the Stanford University campus, with mixed sediments in the upper few tens of meters. Hammer-source data collected during the same deployment as the pulse vibrator data are shown in Fig. 6b. Both are displayed with a 140 to 350 Hz minimum-phase bandpass filter and AGC with a window of 75 ms. They show the same basic features (refracted first arrival, air wave, and some ground roll energy).

Discussion and Conclusions

Direct comparisons of EMvibe data with sledgehammer-source data (Figs. 4 and 6) show that the vibrator device is

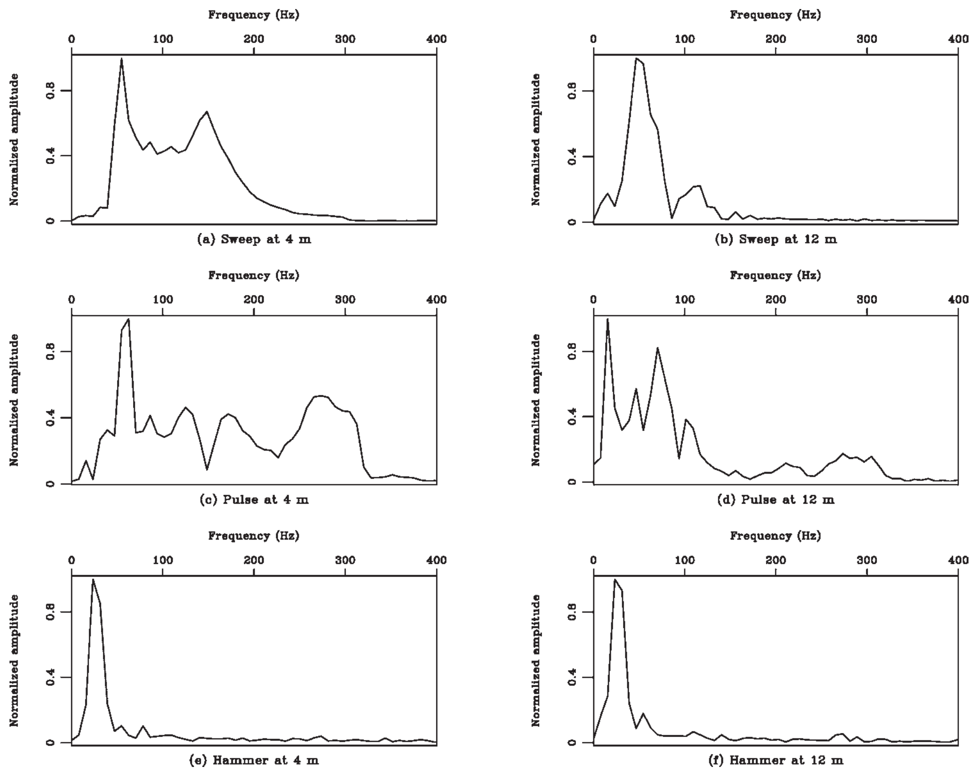

Figure 7. Frequency spectra from geophones at 4 and 12 meters offset. Sweep-signal EMvibe data (14-second sweep 1 to 1,000 Hz, as shown in Fig. 3) at a) 4 m, and b) 12 m. Pulse-signal EMvibe data (same as data shown in Fig. 6) at c) 4 m, and d) 12 m. Hammer-source data at e) 4 m, and f) 12 m. Note that at 4 m, the EMvibe data show a much broader frequency spectrum than the hammer data, and that at 12 m, the sources are more comparable. All data were collected at the same site on the Stanford campus.

effective, but that for these particular experiments the hammer is at least as effective in terms of getting sufficient energy to geophones at 20 m of offset with a minimum of effort and time. However, the frequency content of the sledgehammer data is much narrower than that of the vibrator data, particularly at shorter offsets, as shown in Fig. 7. This figure shows data collected at a site on the Stanford campus at the same location where the data shown in Fig. 6 were collected. Data collected by the geophone at 4 m (Fig. 7a, c, and e) shows a much broader-band signal for both the pulse and the sweep data than for the hammer. Energy reaching the geophone at 12 m (Fig. 7b, d, and f) shows that much of the higher-frequency energy has attenuated at this offset, and that the vibrator and hammer offer similar frequency energy. Visual inspection of the data in Figs. 4 and 6 shows that the hammer is preferable at longer offsets with its greater total energy. Although the spectra shown in Fig. 7 suggest that the pulse is a better source signal than the sweep, visual inspection of Figs. 4 and 6 indicates that the sweep is more effective at offsets beyond a couple of meters.

The data shown here were collected at two test sites with few subsurface layers and no strong reflectors. They show that the EMvibe offers a highly-repeatable broadband signal at offsets less than ~10 m. Testing of the device at a test site with many shallow layers would would likely offer a better comparison with the sledgehammer, and demonstrate its effectiveness in high-resolution reflection work. The device does not replace the sledgehammer, but it does offer an alternative for use in cases where a non-destructive, highly-repeatable, source is required (asphalt evaluations, etc). It does not replace existing portable vibrators (*e.g.*, Ghose *et al.*, 1998; Cardimona *et al.*, 1996), but it is an inexpensive alternative that is well-suited to small studies and teaching demonstrations. Increased numbers of stacks of both pulses and sweeps would extend the EMvibe's range to greater offsets, though it is unlikely that it will be effective beyond a few tens of meters at sites with mainly unconsolidated sediments. The EMvibe shows particular promise for applications such as the Continuous Surface Wave method (Matthews *et al.*, 1996), where a very precise seismic sources is desired to produce surface waves with desired frequency content.

The use of non-linear sweeps would address the problem of the EMvibe's non-linear frequency response and would likely offer significant improvement in the post-correlation wavelet (flatter frequency spectrum leads to a

Table 1. EMvibe components.

Item	Manufacturer	Part	Specs	Approx. cost ($)
Transducer	Clark Synthesis	TST 429	5–800 Hz	500
Amplifier	Crest Audio	FAV900	450 W/chan	500
Sound card	M-Audio	Sonica	24-bit	60
Base plate	self	2.3-cm Delrin sheet	43-cm hexagon	30
Top plate	self	2 × 2.3-cm Delrin	35-cm hexagon	55
Alum. posts	self	2.3-cm Al. rod	12 cm long	8
Total				$1,153

higher-frequency wavelet). A more powerful amplifier would likely produce more energy, though the transducer may not be able to withstand a great deal more input power. And the development of more powerful transducers would obviously lead to improvements in data quality. Other areas for improvement include the sweep correlation procedure; an accelerometer on the EMvibe baseplate would likely provide a better sense of the exact baseplate motion than the raw sweep or the baseplate geophone. Many authors have discussed the use of feedback mechanisms to ensure optimal vibrator/soil coupling (*e.g.,* Sallas, 1984; Schrodt, 1987), but I have neglected this complicated issue and simply attempted to overcome coupling response problems with brute force. Better results would almost certainly be obtained if the EMvibe were equipped with a feedback mechanism.

Specifications

Table 1 shows the major parts of the EMvibe, along with source, basic specifications, and approximate cost. Listed costs are the actual money spent at the time of construction (March 2003). The amplifier was purchased previously-used from a music store. The plastic plates and aluminum rods were machined from scrap stock purchased from local industrial supply stores, so the cost includes only the purchase price of the raw materials. Many other types of plastic offer the rigidity and easy workability of Delrin; any of these would be equally effective. The manufacturer's price for the transducer has been reduced to ~$350 since the time of purchase. Thus the total cost was just over $1,000, but would likely be different for another construction.

Acknowledgments

Essential guidance and supervision for this project were provided by Simon Klemperer and Jerry Harris. The framework of EMvibe was designed and constructed with a great deal of help from the knowledgeable and good-natured staff of the Stanford University Department of Mechanical Engineering Product Realization Lab, to whom the author is very grateful. Valuable design advice was also provided by Adam Pidlisecky and Andrea Les. Thanks also are due to the many people who helped with data collection. Data processing was conducted using the computational resources of the Stanford Exploration Project. Funding for the EMvibe was provided by the Colorado Scientific Society and the Stanford School of Earth Science McGee Fund. This manuscript was considerably improved through suggestions of an anonymous reviewer and the JEEG editors.

References

Anstey, N., 1991, Vibroseis: Prentice Hall, Englewood Cliffs.

Cardimona, S., Kadinsky-Cade, K., Miller, R., Pulli, J., and Turpening, W., 1996, High-resolution seismic reflection survey at Dover AFB: A comparison of three seismic sources: *in* Procedings: Symposium on the Application of Geophysics to Engineering and Environmental Problems, Environmental and Engineering Geophysical Society, 171–180.

Doll, W.E., Miller, R.D., and Xia, J., 1998, A noninvasive shallow seismic source comparison on the Oak Ridge Reservation, Tennessee: Geophysics, **63(04)** 1318–1331.

Ghose, R., Nijhof, V., Brouwer, J., Matsubara, Y., Kaida, Y., and Takahashi, T., 1998, Shallow to very shallow, high-resolution reflection seismic using a portable vibrator system: Geophysics, **63(04)** 1295–1309.

Keiswetter, D.A., and Steeples, D.W., 1995, A field investigation of source parameters for the sledgehammer: Geophysics, **60(04)** 1051–1057.

Matthews, M., Hope, V., and Clayton, C., 1996, The use of surface waves in the determination of ground stiffness profiles: Proc. Instn. Civ. Engrs. Geotech. Engng., **119**, 84–95.

Miller, R., Hancock, W., and Xia, J., 1996, High resolution seismic survey at Mud Mountain Dam, Washington: *in* Abstracts with Programs: Geological Society of America 28th annual meeting, Geological Society of America, 528.

Narbutovskih, S., Michelson, F., Clark, J., and Christensen, E., 1995, High resolution seismic reflection test at the DOE Hanford site: *in* Procedings: Symposium on the Application of Geophysics to Engineering and Environmental Problems, Environmental and Engineering Geophysical Society, 947–951.

Pritchett, W.C., 1994, Why waste money with linear sweeps?: The Leading Edge, **13(09)** 943–949.

Sallas, J.J., 1984, Seismic vibrator control and the downgoing P-wave: Geophysics, **49(06)** 732–740.

Schrodt, J.K., 1987, Techniques for improving Vibroseis data: Geophysics, **52(04)** 469–482.

Sexton, J.L., and Jones, P.B., 1986, Evidence of recurrent faulting in the New Madrid seismic zone from mini-Sosie high-resolution reflection data: Geophysics, **51(09)** 1760–1788.