DESIGN AND APPLICATION OF A MINI-SOSIE SYSTEM

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ABSTRACT

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The main objectives of this study were to (1) design and develop a Mini-SOSIE system, and (2) assess its performance at a test site.

Mini-SOSIE is a light, portable, and nondestructive vibrator that is useful for shallow seismic exploration. During normal operation, the frequency of the vibrator is relatively periodic, leading the autocorrelation to have multiple peaks that affect the correlated shot record; i.e., there is strong interference and thus low resolution and signal-to-noise ratio (SNR). However, randomly varying the throttle using a control system can overcome the periodic nature of the vibrations. To achieve such control, we designed the system and its electronic controller, introducing a pseudo-random control scheme to the Mini-SOSIE system. Field tests verified the validity and efficacy of the designed system. The autocorrelation of the reference trace was better; its SNR was improved by 16.3 dB with respect to normal operation. The new Mini-SOSIE system design provides an alternative for shallow seismic exploration and small engineering exploration. It is also a stable reliable source that can emit a stable repeatable source waveform, which can provide high-quality field data and improve the performance of seismic exploration in the first step.

KEY WORDS: Mini-SOSIE, pseudorandom. resolution, SNR.

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INTRODUCTION

Seismic exploration is an important field of geophysics. Its effectiveness and applicability rely on the seismic source employed, as the excitation signal is a key factor affecting the quality of the recorded data. Near-surface seismic methods are widely used for shallow surveys in civil engineering, earthquake engineering, archeology, and other applications (Feroci et al., 2000; Shtivelman, 2001; Wang, 2002; Yordkayhun et al., 2009; Giustiniani et al., 2008; Pratt et al., 2002). However, in environmentally sensitive areas such as cities or cultural sites, the vibration source must not disturb or damage the surroundings. Mini-SOSIE is compatible with these constraints and has been widely used since 1976 (Driml et al., 2001; Chang and Liu, 2010). It employs a light and portable tamper of the sort used in construction. The principle of the Mini-SOSIE technique consists of sending a coded sequence of impulses into the ground, and measuring the reflected and propagated signals. The impulse signals must be delivered in such a way that the autocorrelation of the sequence closely resembles a unit spike; however, Barbier pointed out that their coding cannot be computed beforehand, so the autocorrelation function must be checked after each transmission (Barbier et al., 1976; Barbier, 1983). Mini-SOSIE is a high-resolution seismic reflection source that has been widely used, including in the New Madrid seismic zone and in northwestern Tennessee (Sexton et al., 1992; Sexton and Jones, 1988). Strong studied the sign-bit Mini-SOSIE stacking concept and found the results improved when there was a relatively high level of random noise (Strong, 2003; Strong and Hearn, 2004). In the normal operation of a Mini-SOSIE, a tamper produces a sequence of periodic impacts via an operator controlling the throttle, resulting in strong correlation noise. Pseudorandom coding (Sarwate and Pursley, 1980; Stasev et al., 2007) provides an obvious advantage in that its correlation wavelet is simpler than conventional approaches such as swept-frequency vibroseis and a sinusoidal carrier signal of constant frequency (Maxwell et al., 2010). Pseudorandomness has been successfully used to reduce interference noise in simultaneous vibroseis surveys (Nasredin et al., 2012; Becquey, 2002; Sallas et al., 2008, 2011). A vibrator must do more than simply vibrate: it should generate vibration signals of good quality. Good field data will save many steps of data processing and provide a clear overview of the seismic profile. Therefore, much effort should be put into the design of the vibrator, especially its control scheme and working mode.

In this study we analysed the normal operating mode of a Mini-SOSIE. To reduce the interference noise and improve its working condition, the Mini-SOSIE machine was modified by introducing a pseudorandom electronic control. Finally, field testing verified the effectiveness of the designed system.

MINI-SOSIE SYSTEM DESIGN

Mini-SOSIE uses a tamper (of the type commonly used in construction) as the source of repetitive impact. The MT-72FW (Mikasa Sangyo Co., Ltd. Japan) vibrator used in this study is shown in Fig. 1. In order to achieve a better control method, it is necessary to analize its working principle.

Fig. 1. The MT-72FW vibrator tamper used in this study.

The vibrator comprises an air-cooled four-stroke engine, crankshaft, centrifugal clutch, gears, coil spring, and a baseplate. The engine drives the crankshaft, and the centrifugal clutch makes the gear decelerate, thus converting the rotary motion into up-and-down motion of the baseplate. A strong coil spring is located beneath the engine. The motive forces and gravity combine to create a powerful impact on the ground.

During normal operation, the operator controls the centrifugal clutch by opening the throttle, which gradually increases the amount of fuel injected, and consequently the clutch speed and impact velocity, causing movement of the baseplate of the tamper. The magnitude of the impact depends on the engine speed, which is controlled by the amount of fuel injected. Setting the throttle to maximum results in the strongest impact, and setting the throttle to minimum stops the movement. A physical model of the vibrator is shown in Fig. 2.

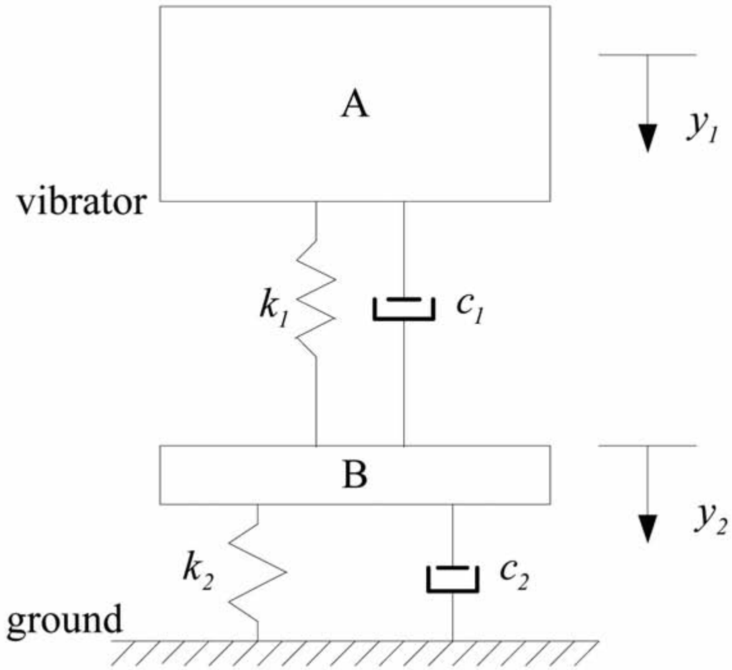


Fig. 2. Physical model of the vibrator.

In the figure, A represents moving parts, its mass is m; B is the substrate, its mass is m1; k_1 and k_2 are the spring stiffness coefficients between the moving parts and the baseplate and between the substrate and the ground, c_1 and c_2 are damping coefficients; F_a and F_g are the vibrator excitation force and the output force of the system, respectively; and y_1 and y_2 are the vertical displacements of the moving parts and the substrate, respectively. Although the vibrator is a complex and high-order system, considering its structural characteristics it represents a “quality–spring–damper system model”.

During vibration, the vertical position of A is Z_1, the vertical position of B is Z_2, and F_m is the force of the baseplate. Only when the vibrator jumps up and falls down back to the ground will there be force, and the physical model in Fig. 2 will be applicable. Under such conditions, the dynamic equation of A and B is

$$m\ddot{Z}_1 + k_1(Z_2 - Z_1) + c_1(\dot{Z}_2 - \dot{Z}_1) = F_m S_a(t) \quad , \tag{1}$$

and

$$S_a(t) = \frac{\sin t}{t} \quad . \tag{2}$$

In conventional use, the operator controls the vibrator by varying the throttle as randomly as possible. However, this control method is neither accurate nor stable. To meet the requirements of pseudorandom control and to simplify operation, the throttle controller needs to be designed with electronic, rather than manual, control. Fig. 3 shows the structure of the throttle controller. A small motor added to the throttle control mechanism moves the throttle back and forth across its full range. The motor is controlled by a driver module.

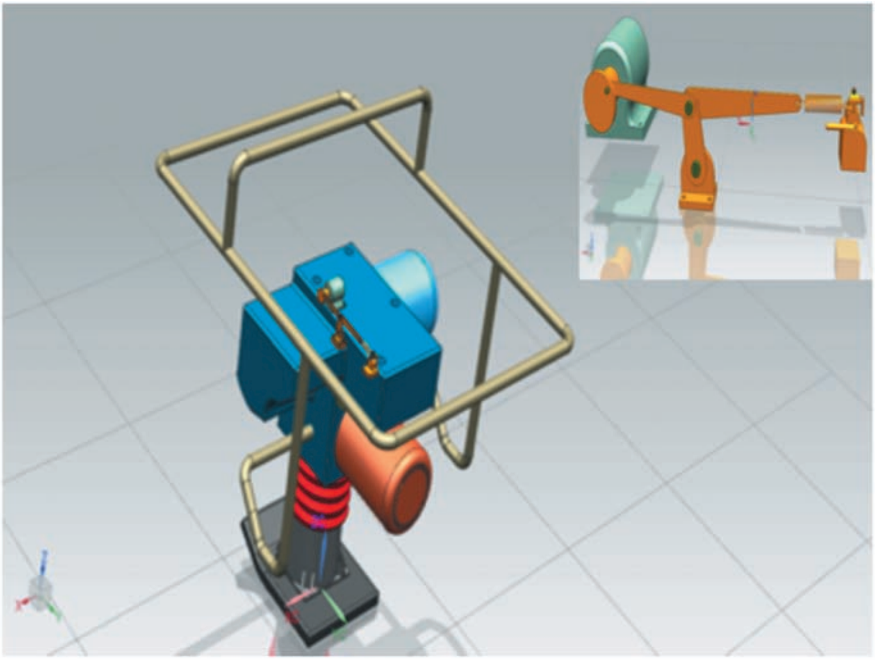


Fig. 3. Structure of the throttle controller.

The principle diagram of the electronic control system is shown in Fig.4. The FPGA (Field－Programmable Gate Array) is the main control chip, and is used to generate and identify the pseudorandom sequence. When the code is 1, it sends a pulse signal, and when the code is −1 there is no signal. Parameters such as the pseudorandom sequence and coding delay time are entered via the human interface, which also displays the working state. Vibrating signals are collected at the baseplate sensor, which also gives feedback to the FPGA controller to monitor the performance of the system in real time.

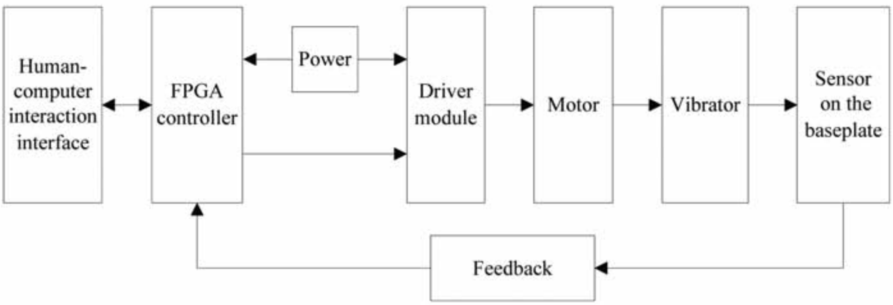


Fig. 4. Electronic control system.

After testing, the system's parameters were established as follows:
(1) Input voltage: 12 V.
(2) Power consumption of the controller: <1 W.
(3) Interval of up–down output signals: <1 μs.
(4) Coding delay time: can be set arbitrarily.

RELATED RESEARCH

Signal characteristic analysis

The basic principle of seismic exploration is that a vibrator sends vibration signals into the ground, and the signals are then recorded by geophones. Processing and analyzing these data can give information about the subsurface geologic structure. As the vibrator is the source of the seismic waves, it is necessary to analyze the seismic waves. During normal operation, the vibrator runs at full throttle. Fig. 5 shows the signal recorded during a period of 1 s.

The amplitude and period of the vibration are both stable, indicating that the vibrator hits the ground at a relatively constant rate. There are about 12 seismic wavelets per second. The autocorrelation of the signal is shown in Fig. 6.

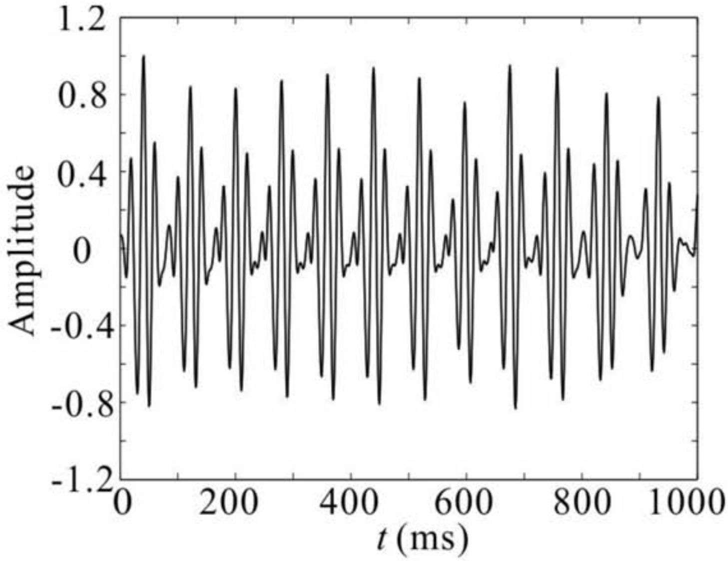


Fig. 5. Vibration signal during 1 s.

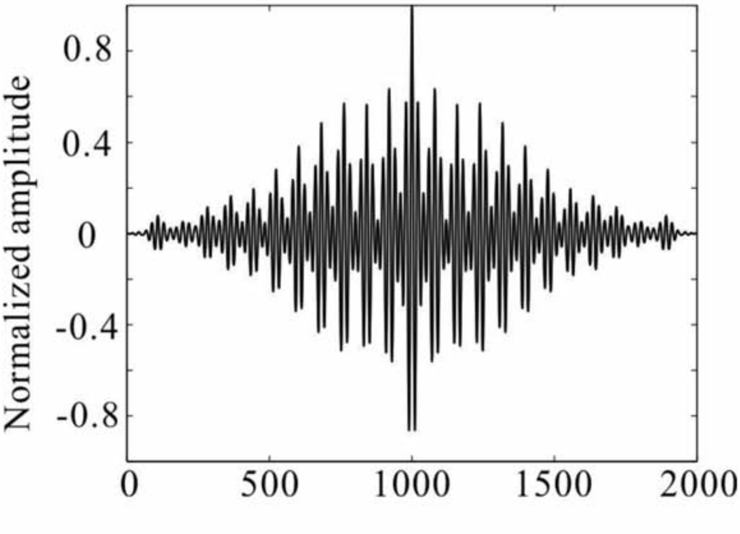


Fig. 6. Autocorrelation result of the signal in Fig. 5.

The autocorrelation pulse of this input signal is not a single peak. The strong secondary peaks on either side of the main peak are due to the periodic nature of the vibrator. If any frequency is repeated, the autocorrelation shows multiple peaks, which would contaminate the correlated shot record. This problem occurs when using regular vibrators, so consideration of the autocorrelation of the reference trace is important in this type of survey.

Basic principle

To solve the autocorrelation problem, the impact sequence must be sufficiently randomized so that the interval between impacts is never consistent. We used a pseudorandom method here. The principle of pseudorandomness is as follows (Peinado and Subater Fuster, 2013; Dean, 2012, 2014). A pseudorandom sequence is composed of two elements (1 and −1) that are usually termed bits or code, and their duration is the bit length. If q is prime, and F_q is a collection composed of non-negative integers smaller than q, the n-order primitive polynomial is

$$g(x) = \sum_{i=0}^{n} c_i x^i (c_i \in F_q, c_0 \neq 0, c_n \neq 0) \quad . \tag{3}$$

Supposing $(a_0, a_1, ..., a_{n-1})$ is the nonzero initial vector of F_q, according to the formula

$$a_i = -c_{n-1}a_{i-1} - c_{n-2}a_{i-2} - ... - c_0 a_{i-n} \ (i = 0,1,...) \quad . \tag{4}$$

We can obtain a binary sequence $\{a_k\}$ of length 2^n-1, where n is the length of the original sequence. The autocorrelation of a pseudorandom sequence is

$$R(j) = \begin{cases} 2^n - 1, j = 0(mod(2^n - 1)) \\ -1 \ , j \neq 0(mod(2^n - 1)) \end{cases} \quad . \tag{5}$$

The autocorrelation has a shape very close to a perfect pulse, as the value is 2^n-1 at lag = 0, and −1 at others. Fig. 7 shows the autocorrelation of a pseudorandom sequence for $n = 6$.

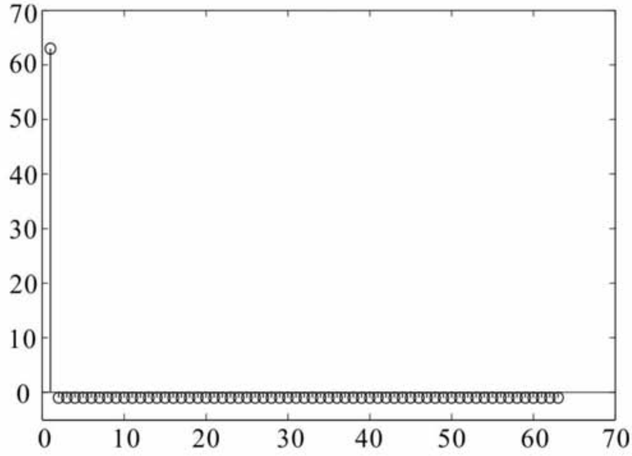


Fig. 7. Autocorrelation of a pseudorandom sequence for $n = 6$.

During the operation of the Mini-SOSIE, it usually produces a vibration of relatively stable frequency. The amplitude is controlled by the speed of the engine, which has a positive linear relationship with the throttle input. Therefore, this work developed an excitation signal generator to control the throttle. Pseudorandom control of the vibrator was achieved through modulation between the pseudorandom coding and the vibrating state: a code state of 1 generated a pulse signal and the vibrator began to work, while a code state of −1 gave no pulse signal and the vibrator stopped working. To examine the modulation process, Fig. 8 shows the corresponding pulse signal collected using a sensor on the baseplate.

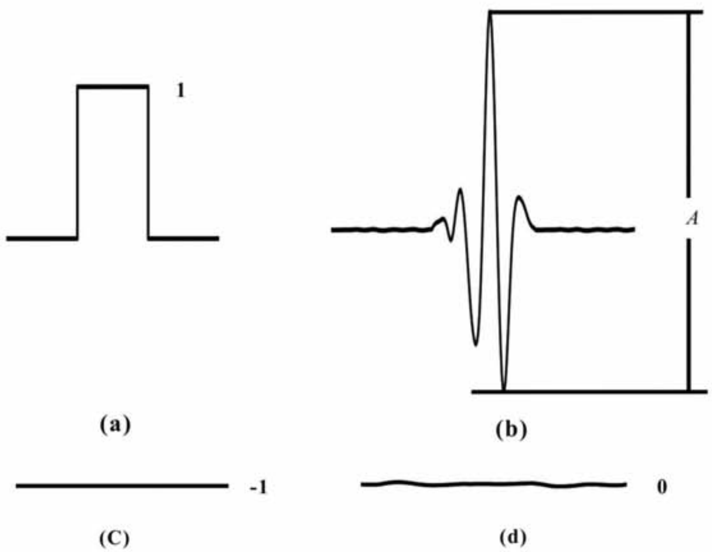


Fig. 8. Coding and the corresponding signal collected from a sensor on the baseplate: (a) code value 1 and (b) its corresponding pulse signal (A is the amplitude of the signal); (c) code value −1 and (d) its corresponding pulse signal.

Supposing that $y = A*\text{s\_wavelet}(f)$ is the wavelet signal acquired by the Mini-SOSIE, A is the amplitude of the vibration signal, and f is its frequency. If $a(i)$ is the coding sequence, modulation between the pseudorandom coding and the vibrating state can be expressed by the following formula:

$$y = \begin{cases} A*\text{s\_wavelet}(f), a(i) = 1 \\ 0 \qquad , a(i) = 0 \end{cases} \quad . \tag{6}$$

SOURCE SIGNATURE AND PERFORMANCE

This Mini-SOSIE system is expected to be a stable and reliable source, and its electronic control system proved to be sophisticated and accurate. The new Mini-SOSIE is an environmentally friendly seismic source because it does not destroy the environment or buildings. In addition, it is easily transported and can be used in restricted environments, as it can be moved by a single operator across flat terrain. The simple operating system makes it easy to maintain, and the smart electronic control system makes it easy to operate.

The seismic source is crucial to seismic exploration, and the signals emitted by the source determine the effectiveness of the exploration. Therefore, it is important to analyze the original signals emitted by the Mini-SOSIE in this research.

PSEUDORANDOM APPLICATION AND FIELD TESTS

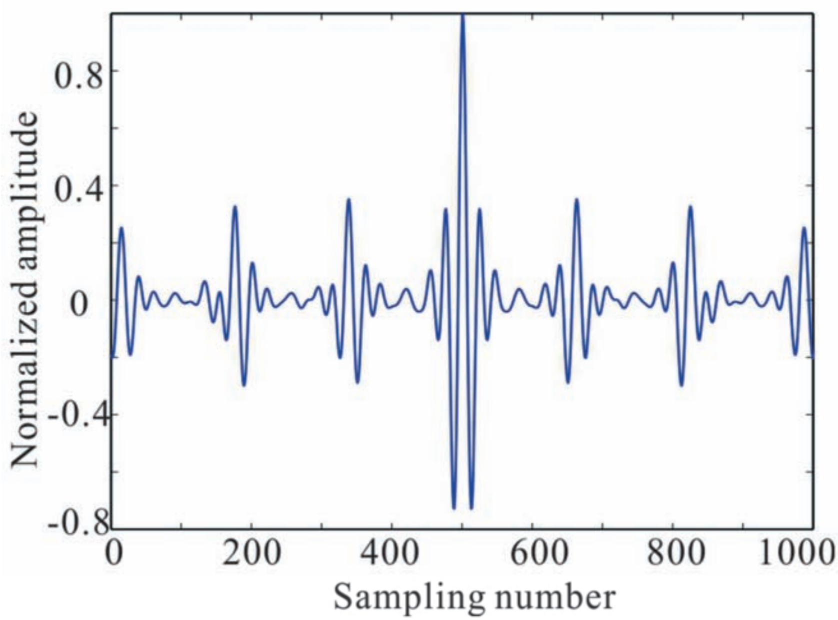
The effectiveness of the pseudorandom method was assessed in a high-resolution near-surface seismic survey. We used a Geometrics GEIST-II system with 72 channels for data acquisition and a MT-72FW tamper as the seismic source. The geophones (JF-20DX-10Hz) were chosen on the basis of their availability. They were placed at 2 m intervals, and the sampling rate was set at 1 ms. In order to observe the raw signal characteristics as accurately as possible; no recording filters or gain were applied. The field tests employed both operating modes, using the same acquisition scheme in each case. All tests were conducted at the same field site at Changchun, Jilin, China, on a grass lawn having mixed sediments in the upper few tens of meters, and there is little traffic noise.

In seismic exploration, the side lobe of the correlation wavelet is defined as the noise of the signal, as it depends on the shape of the scanning signal (Cunningham, 1979). Fig. 9 shows the autocorrelation results of the reference for the two different operating modes.

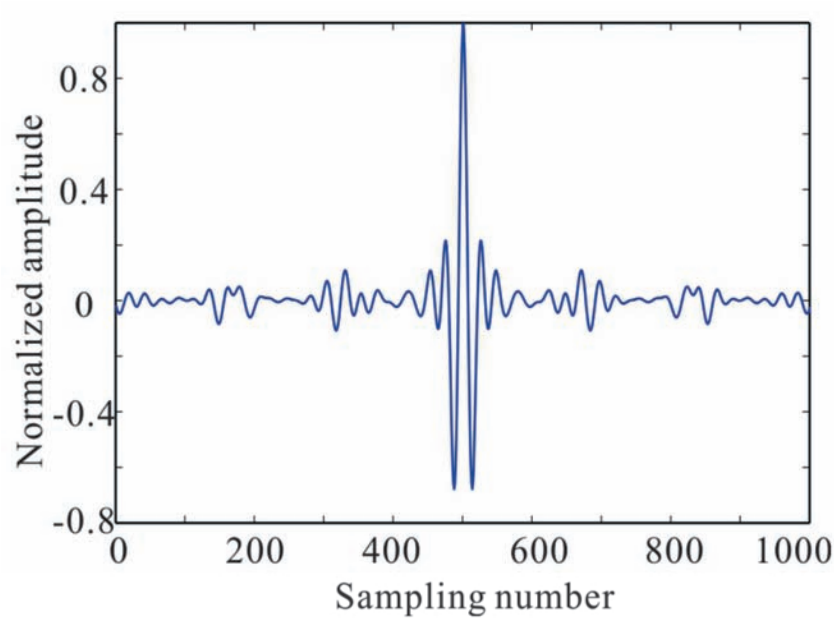
The calculated ratios between the side lobe and the main lobe and between the related interference and the main lobe are listed in Table 1.

Table 1. Ratio of the side lobe to the main lobe, and of the related interference to the main lobe.

Operation modes	Normal operation	Pseudorandom operation
Ratio of side lobe to main lobe (dB)	9.1	-19.3
Ratio of related interference to main lobe (dB)	-9.7	-26.0



(a) Normal operation mode

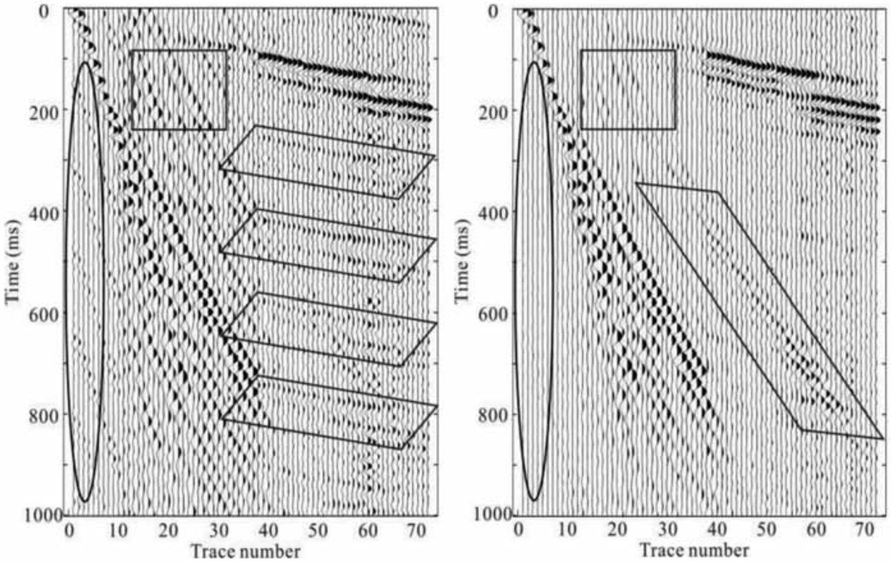


(b) Pseudorandom operation mode

Fig. 9. Autocorrelation results for (a) normal and (b) pseudorandom operation.

Interference with pseudorandom operation was 16.3 dB lower than with normal operation, for the reason that it did not use repeated frequencies. The results indicate that the pseudorandom operation mode can suppress interference effectively, which can improve the SNR of the seismic data.

Data from the impulse seismic source must be correlated with a pilot source to compress the source time to a spike before the data can be interpreted. We used the data from the geophone located 1 m from the vibrator as the pilot trace. Data are correlated with the raw sweep and stacked to produce each shot record. Fig. 10 shows the shot records of the seismic data collected using the two different operating modes.

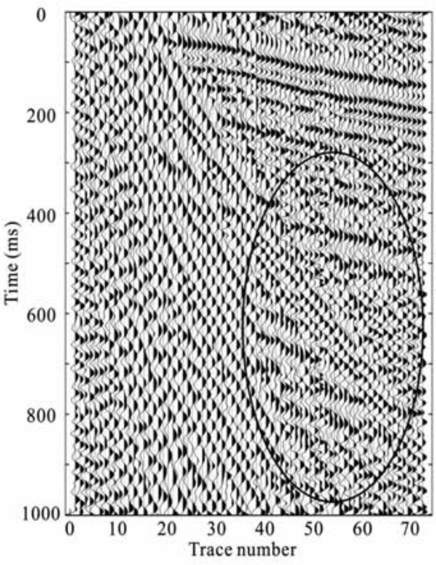


(a) Normal operation mode (b) Pseudorandom operation mode

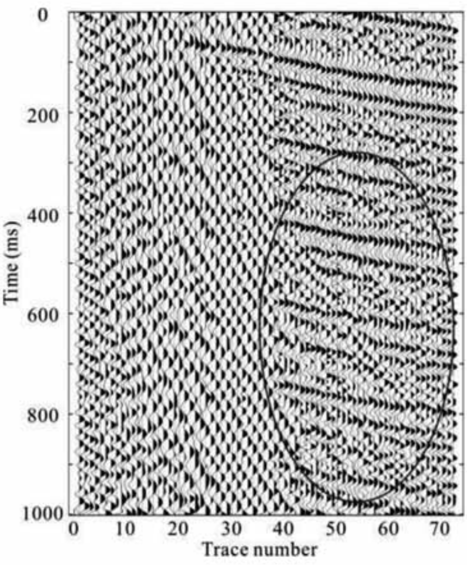
Fig. 10. Shot records of the seismic data collected during (a) normal and (b) pseudorandom operation.

During the two modes of operation, the surface waves appear well developed and the direct waves are clear. However, marked interference (circled in oval and rectangle parallelogram in Fig. 10) and multiple waves (circled in parallelogram) are apparent during normal operation. In contrast, the shot record in Fig. 10(b) for pseudorandom operation shows improved clarity, with little interference, demonstrating the effective reduction of interference and the suppression of multiple waves, which improved the resolution of the seismic data.

The main purpose of this paper is to design a Mini-SOSIE system that can emit vibration signals of good quality; i.e., the field data are of higher quality than those from a normal Mini-SOSIE system. However, the study would be more complete if data processing were included to reduce noise or interference. As the seismic wave spreads from its source, its amplitude decays in proportion to the reciprocal of the distance from the source. Therefore, whenever we display the seismic data, it is desired to boost weak signals by adding more gain to the data. Automatic-gain-control (AGC) process is usually used to increase the amplitudes of the data for display or processing purposes. The critical parameter of AGC is the length of the AGC window; i.e., the time-band within which the amplitudes are normalized. The highest amplitude within this window will strongly influence the normalization. If the window is too small, every signal within it will be changed, whereas if it is too large there will be no significant effect on the amplitude of the data. In this study the length of the AGC window is 60 ms; the shot records after AGC processing are shown in Fig. 11.



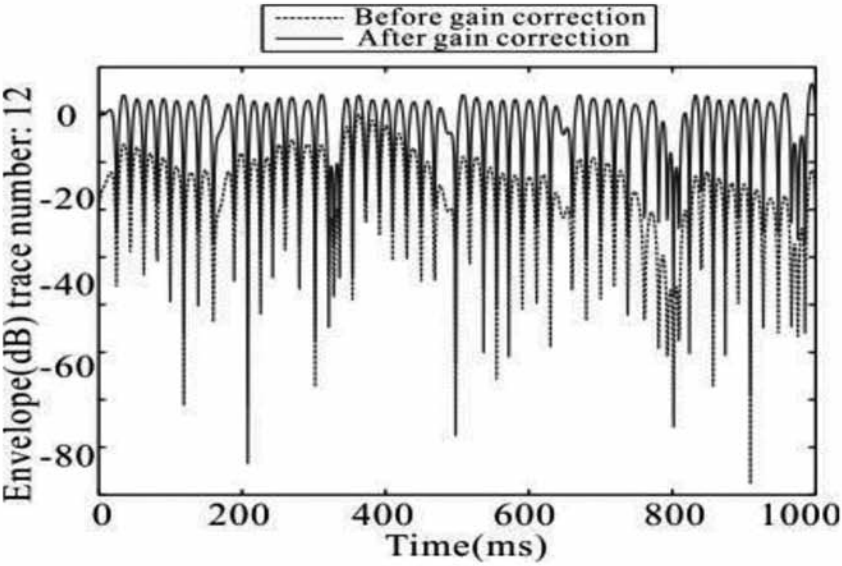
(a) Normal operation mode



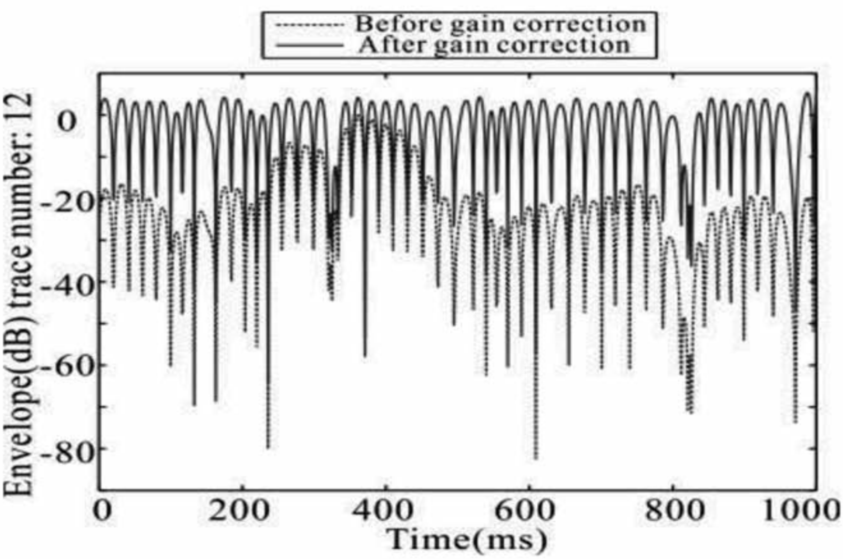
(b) pseudorandom operation mode

Fig. 11. Shot records after adding AGC processing of the seismic data collected during (a) normal and (b) pseudorandom operation (both are 60 ms time window).

A comparison of Figs. 11(b) and 11(a) shows that multiple waves are reduced (circled in oval). Pseudorandom operation clearly improved the quality of the seismic data. We randomly selected traces of the two different operation modes and added AGC processing (window length 60ms). The results are shown in Fig. 12.



(a) The 12th trace of normal operation mode

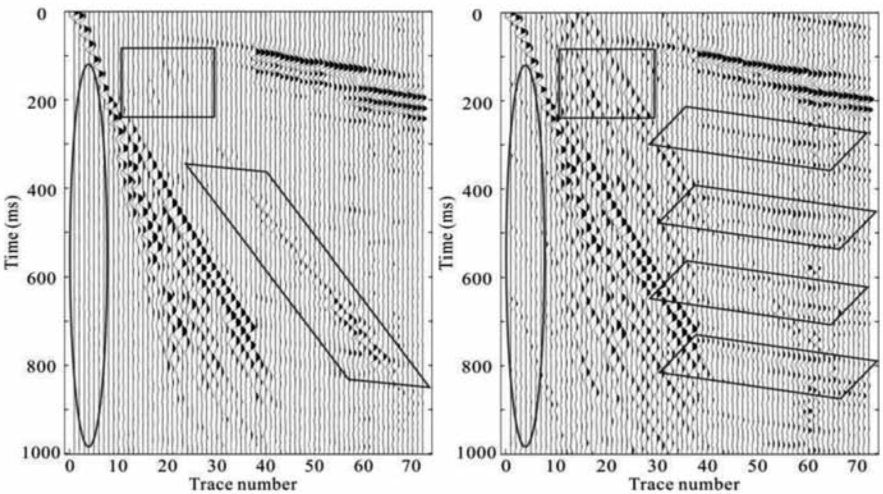


(b) The 12th trace of pseudorandom operation mode

Fig. 12. The 12th trace of the two different operation modes after adding AGC processing (a) normal and (b) pseudorandom operation; the dotted line is the data before gain correction, the solid line is the data after gain correction (both are 60 ms time window).

The amplitude gaps are due to the fact that the AGC window at these time shifts contains both low-amplitude noise and high-amplitude seismic signal and dividing by their RMS (root-mean-square) value amplifies the signal and attenuates the noise.

In seismic exploration, random noise is a kind of interference wave with a wide frequency band. It has seriously effects and is the main factor affecting the quality of seismic data. Wiener filtering is useful for retaining the edge parts of the image and other high frequencies, as it can adjust the parameters according to differences in the local image. Such filtering is therefore helpful in eliminating random noise. Data processing used neighborhoods of size 3×3 to estimate the local seismic data's mean and standard deviation. The shot records after adding Wiener filter processing are shown in Fig. 13. This approach effectively suppressed surface waves and random noise.



(a) Normal operation mode (b) pseudorandom operation mode

Fig. 13. The shot records after adding Wiener filter processing (a) normal and (b) pseudorandom operation.

Comparison with Fig. 10 indicates that Wiener filter processing caused the multiple waves and surface waves to decay (circled in parallelogram), and suppressed interference (circled in oval and rectangle). Overall, the filtering helped to improve the quality of the seismic data.

Fig. 14 shows spectra for the two different operating modes. The bandwidth in each case is 5–110 Hz. The signal obtained from pseudorandom operation decays more slowly, and the frequency bandwidth is wider than the signal obtained from normal operation, indicating a higher resolution.

Fig. 15 shows frequency–wavenumber spectra for the two different operating modes. The slight difference between them indicates that pseudorandom operation has more concentrated energy and less interference or noise, giving richer frequency content.

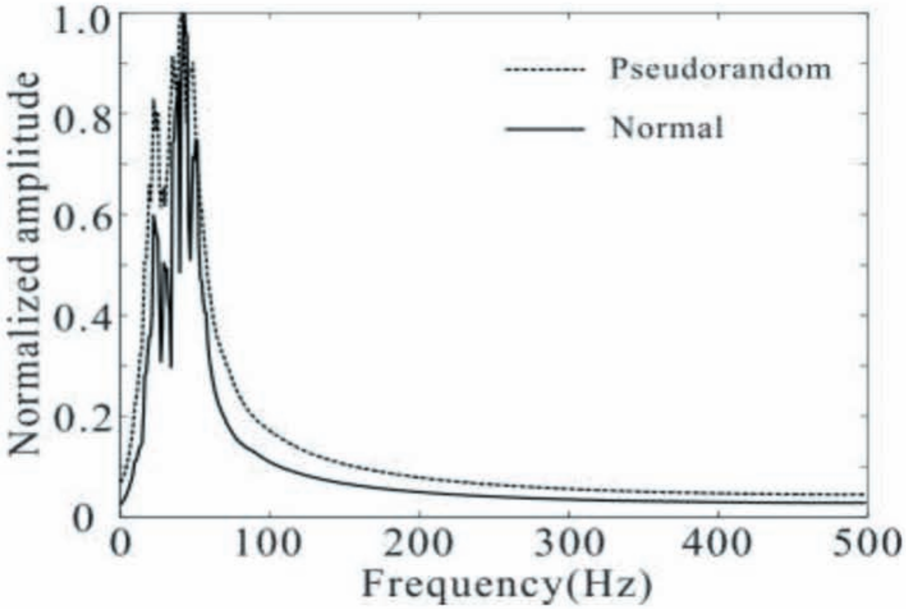


Fig. 14. Spectra of (solid line) normal operation and (dotted line) pseudorandom operation.

DISCUSSION AND CONCLUSION

This study presents a newly designed Mini-SOSIE system for shallow seismic exploration. The developed seismic reflection source is easily transported and can be used in restricted environments. The simple operating system makes it easy to maintain, requires little manpower, and is expected to be highly reliable due to the electronic control system. In comparison with the normal operating mode, pseudorandom operation effectively suppressed interference, and thus improves the SNR and resolution of the seismic data. This system is a good choice for shallow seismic exploration, is environmentally friendly, and can supply sufficient energy for surveying. Although this study demonstrates that the electronic control system is reliable and the source performance is better with the analysis of the field data. The work would be more complete if more data processing methods were used to analyze the seismic data. Overall, this study shows that field data of high quality can be obtained from the designed Mini-SOSIE system.

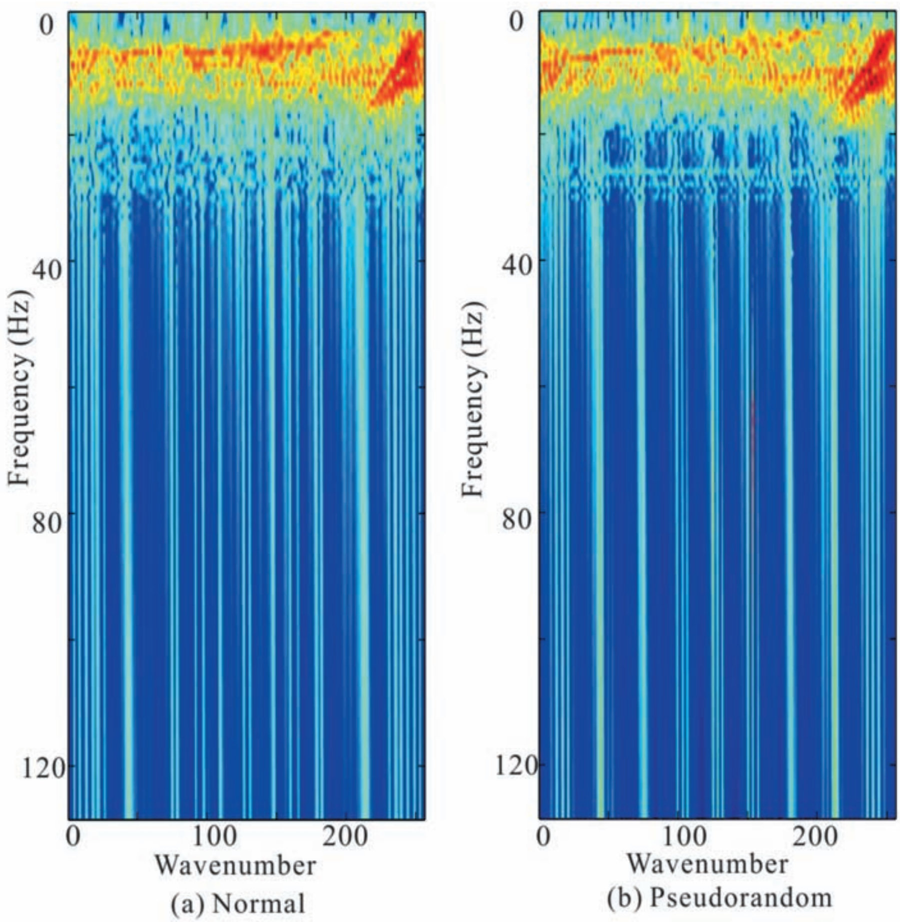


Fig. 15. Frequency–wavenumber spectra for (a) normal and (b) pseudorandom operation.

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