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Reverberation Generated by Sequential Underwater Explosions[1]

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Abstract—In order to obtain long-time reverberation, an innovative experiment is operated, using a sequence of explosions with a interval time. The relationship between reverberation generated by single explosion and a sequence of explosions is discussed. The data are obtained from the experiment, then analyzed with method of wavelet transform, conclusion is obtained that power generated by sequence of explosions with different interval time spreads uniformly at low frequency range, unequally at high frequency range.

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INTRODUCTION

Underwater explosions can be adapted as acoustic sources, Weston (1960) made research on the special nature of the underwater explosion signal, including effects due to surface cavitations, charge size and explosion depth. The acoustic characteristic of shock wave was studied by Pan (1999), it is short-time and wide-brand, the power at each frequency is high, and transformation efficiency from chemical energy to acoustic energy is high. Using the wavelet method, acoustic characteristic of explosion signal was analyzed by Wu (2008), the results show that the power of the sound pulse at each frequency is high, and the power spreads mainly at frequencies below 10 kHz. Vadov (2005) made experimental studies on the time structure of bistatic reverberation generated by underwater explosion in the long-range, particularly on the classical signal quartets accompany with noise signal called prereverberation.

However, the duration of reverberation generated by single explosion is relatively short, in order to obtain long-time reverberation, in this paper, an innovative experiment is operated, using a sequence of explosions with an interval time. Reverberation generated by a sequence of explosions is combination of reverberation generated by several single explosions.

Following the introduction, we describe the experiment and the bottom topography of the experiment site. Then we discuss the relation between reverberation generated by a single explosion and a sequence of explosions. After that, effects of interval time on reverberation are analyzed. Finally, some conclusions are presented.

[1] The article is published in the original.

EXPERIMENTAL EQUIPMENT AND GEOMETRY

The experiment was performed in a lake, in the spring season, with a negatively refracting medium. The vertical sound speed profile measured during the experiment is shown in Fig. 1. The wind speed was 3–4 m/s, the lake state was not higher than Beaufort 3. Figure 2 shows a schematic of the geometry for the underwater explosions experiment. The hydrophone was deployed from ship I to a depth of 55 m and it operates across the frequency band 1 Hz–50 kHz with a sensitivity of -202 ± 3 dB re 1 μPa. The sequence of explosions was deployed from ship II, the top explosion was at the depth of 40 m, the distance between every two explosions was 3 m, each explosion was a charge of 20 g TNT, the interval time T was controlled with a blasting circuit. Both ships, positioned by GPS, were separated in range by about 850 m. The seabed was nominally flat, with cobble and gravel, with an average water depth of 140 m.

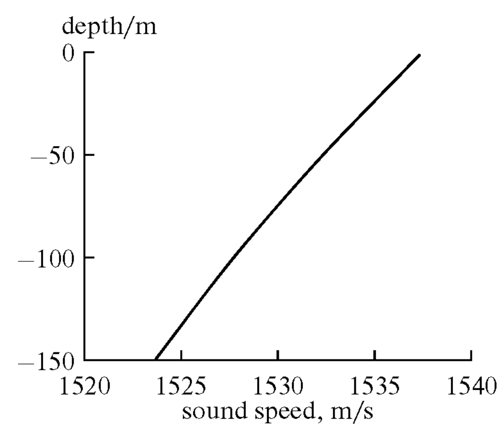

Fig. 1. Vertical sound speed profile during the experiment.

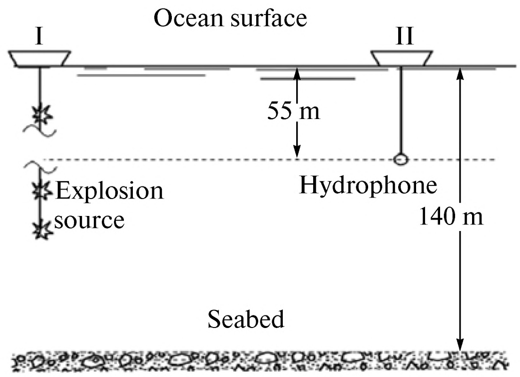

Fig. 2. Schematic of experimental geometry for underwater explosion experiment.

REVERBERATION GENERATED BY A SEQUENCE OF EXPLOSIONS

Reverberation Generated by a Single Explosion Source

At the beginning of the experiment, preliminary experiment of single explosion was operated. The experimental design was the same as above, while the single explosion was deployed to a depth of 100 and 130 m. Signals generated by the two single explosions is shown in Figs. 3a and 3b, and comparison of reverberation generated by the two single explosions is shown in Fig. 3b. In Fig. 3, the pressures are different with depth, and the peak pressure at the depth of 130 m is higher, the reverberation level is almost unaffected by depth.

Reverberation Generated by a Sequence of Explosion Sources

Because the duration of reverberation generated by a single explosion is short, we use a sequence of explosions with an interval time to obtain long-time reverberation. Because the reverberation is unaffected by depth, as noted above, we assume that, the reverberation generated by each single explosion at different depth is uniform. According to the assumption, reverberation generated by a sequence of explosions without interaction is illustrated in Fig. 4.

After the first explosion was detonated, the signal generated by the explosion propagated to the seabed, then propagated to the hydrophone after bottom scattering. Reverberation generated by the first explosion arrived at the hydrophone at time t, which is expressed as $RL(t)$. After the interval time T, the second explosion was detonated, reverberation generated by the second explosion arrived at the hydrophone at time t expressed as $RL(t-T)$, and so forth. Reverberation at

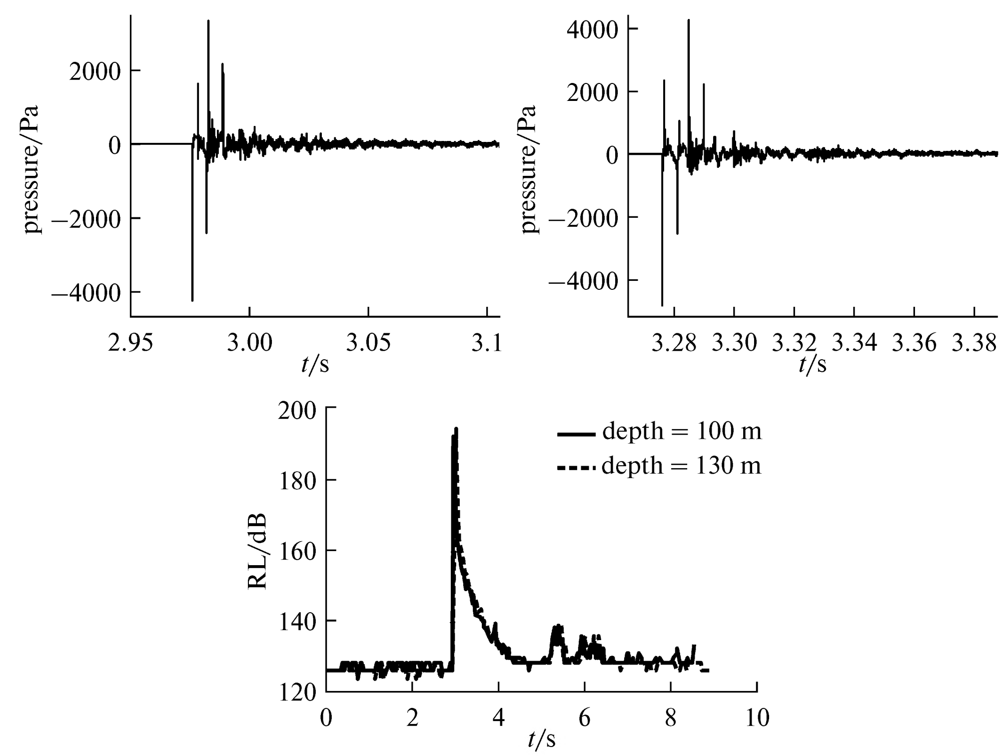

Fig. 3. Signal and reverberation generated by a single explosion.

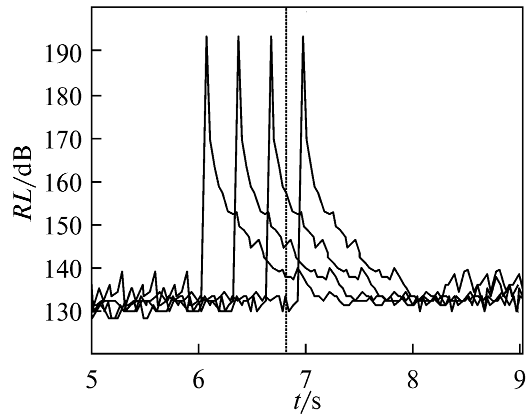

Fig. 4. Reverberation generated by a sequence of explosions without interaction.

time t is combination of reverberation generated by several single explosions, which can be written as

$$RL(t) = RL(t) \oplus RL(t-T) \oplus RL(t-2T) \oplus \ldots \oplus RL[t-(N-1)T]. \quad (1)$$

Here $\oplus$ is an operator which can be described by the following equation

$$\oplus = 10\log \sum_{n=1}^{N} 10^{RL_n[1-(n-1)T]/10}. \quad (2)$$

The essence of the operator is to calculate the sum of pressure level conversed from the reverberation level, then converse the sum back to the reverberation level.

The number of explosion sources contributing to reverberation received at time t can be determined by the following expression

$$N = \left[\frac{t-t_{\min}}{T} + 1\right]. \quad (3)$$

Here [ ] is the Gauss symbol to get the greatest integer which is less than or equal to the number in the square brackets.

ANALYSIS OF EXPERIMENT DATA

During the experiment, we control the interval time by using a blasting circuit. Because of the failures of few explosion sources, several sets of data were collected unexpectedly. In order to research the effects of

Distribution of frequency band

Low frequency wavelet coefficients	Frequency band range	Frequency division	Frequency of the signal, kHz	High frequency wavelet coefficients	Frequency band range
a1	0~0.5	1/2	384	d1	0.5~1
a2	0~0.25	1/4	192	d2	0.25~0.5
a3	0~0.125	1/8	96	d3	0.125~0.25
a4	0~0.0625	1/16	48	d4	0.0625~0.125
a5	0~0.03125	1/32	24	d5	0.03125~0.0625
a6	0~0.015625	1/64	12	d6	0.015625~0.03125

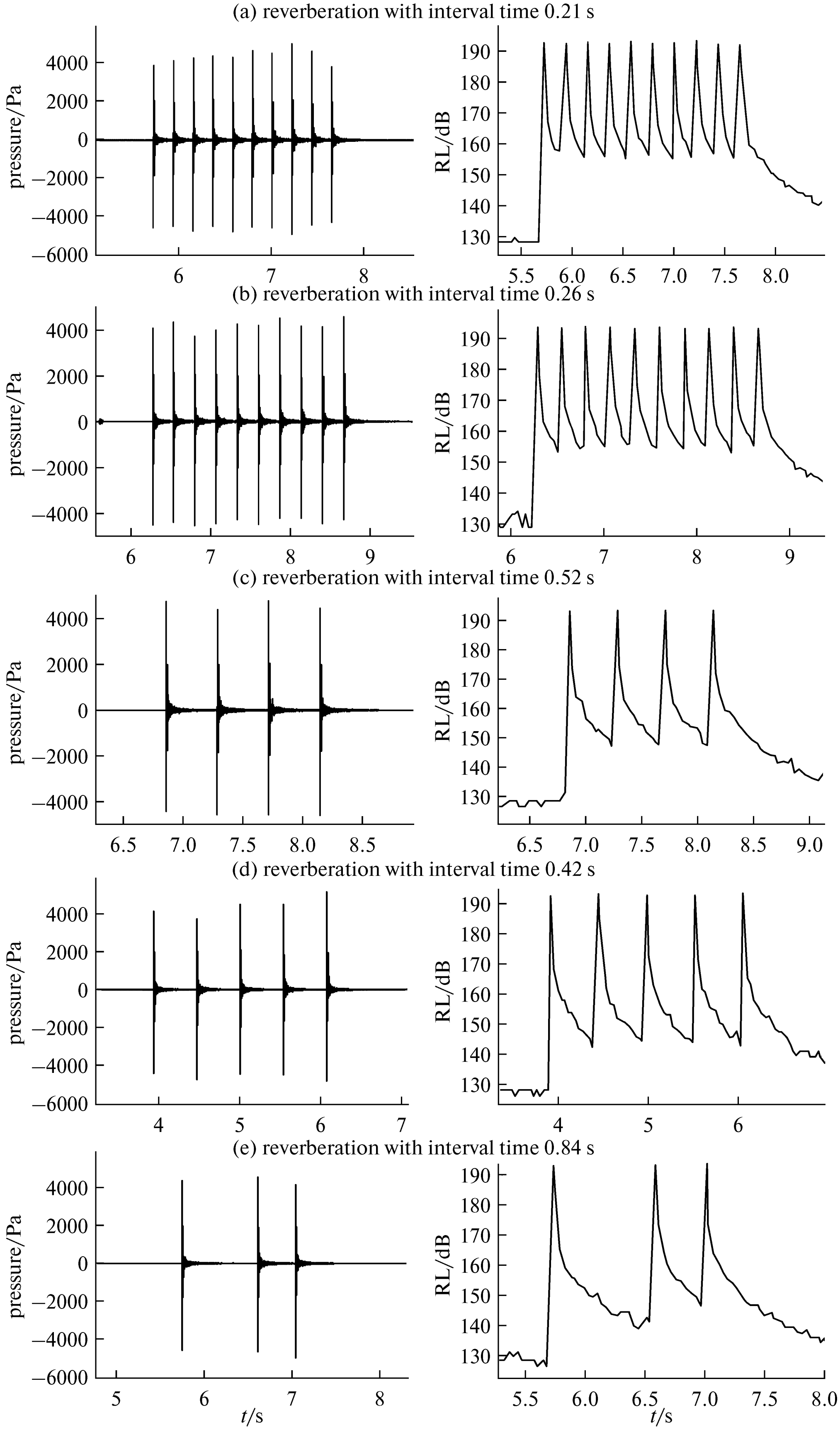

Fig. 5. (a) reverberation with interval time 0.21 s; (b) reverberation with interval time 0.26 s; (c) reverberation with interval time 0.52 s; (d) reverberation with interval time 0.42 s; (e) reverberation with interval time 0.84 s.

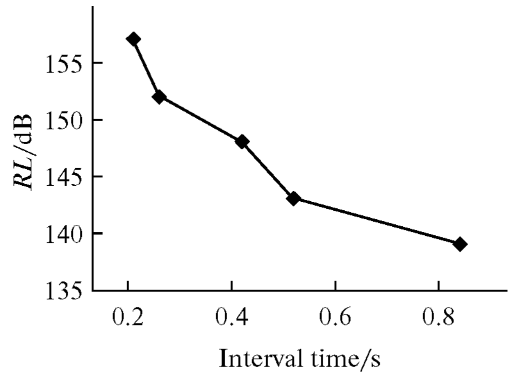

Fig. 6. reverberation levels at the trough.

interval time T, time-domain analysis and frequency-domain analysis is operated.

Time-Domain Analysis

Figures 5a and 5b show signal and reverberation generated by 10 explosion sources with interval time 0.21 and 0.26 s. Figure 5c shows signal and reverberation generated by 5 explosion sources with interval time 0.52 s. Figure 5d shows signals generated by 5 explosion sources with interval time 0.42 s, when the first explosion source failed. Figure 5e shows signals generated by 5 explosion sources with interval time 0.41 s, when the second and fifth explosion sources failed.

Observing graphs above in Fig. 5. The reverberation levels at the indentions with different interval time are shown Fig. 6, which indicates obviously that reverberation level at the indentions decreases as the interval time increases, and the amplitude is 15 dB, which cannot be insignificant.

Frequency Domain Analysis

Figures 5a and 5b have the same number of explosion sources but the interval time. Discrete wavelet transform is operated on the data of Figs. 5a and 5b, using the Daubechies 6 wavelet filter, then Welch spectral estimation is operated, and a comparison is shown in Fig. 7. The signal is decomposed to the sixth scale, where a1, a2, a3, a4, a5 and a6 represent the wavelet coefficient of lower frequency component of the first, second, third, fourth, fifth and sixth scale separately, d1, d2, d3, d4, d5 and d6 represent the wavelet coefficient of higher frequency component of the first, second, third, fourth, fifth and sixth scale separately. Frequency bands of each scale are shown in table.

From the first to the third scale, considering data of Fig. 7a, energy of explosion signal distributes mainly at low frequency range a1, a2 and a3, from the fourth to the sixth scale, power spectrum of explosion signal at both low and high frequency ranges reach unanimity, especially at the sixth scale, both of them get a good approximation, which indicates that, power generated by explosions spreads mainly below 10 kHz.

Comparison of power spectrum of Figs. 7a and 7b is processed from the first scale to the sixth scale. From the first scale to the third scale, the power generated by sequence of explosions with longer interval time is higher than that with shorter interval time; From the fourth scale to the sixth scale, power spectrum of Figs. 7a and 7b tends to overlap, which indicates that power generated by sequence of explosions with different interval time distributes uniformly at low frequency range, unequally at high frequency range.

In Figs. 7c–7e, although the number of explosion sources and interval time are both different, in essence, the difference is interval time, so it can be concluded that power spectrum of explosion signal reaches unanimity at low frequency range, the power generated by sequence of explosions with longer interval time is higher than that with shorter interval time.

CONCLUSIONS

In order to obtain long-time reverberation, an innovative experiment is operated, using a sequence of explosions with a interval time. The relation between reverberation generated by a single explosion and a sequence of explosions is discussed, reverberation generated by a sequence of explosions is combination of reverberation generated by several explosions. Then, the experiment data is analyzed and conclusions are obtained. Reverberation level at the trough decreases as the interval time increases. Concerning one set of data, power generated by underwater explosions spreads mainly below 10 kHz. Comparison of power spectrum of two sets of data with different interval time indicates that, power generated by sequence

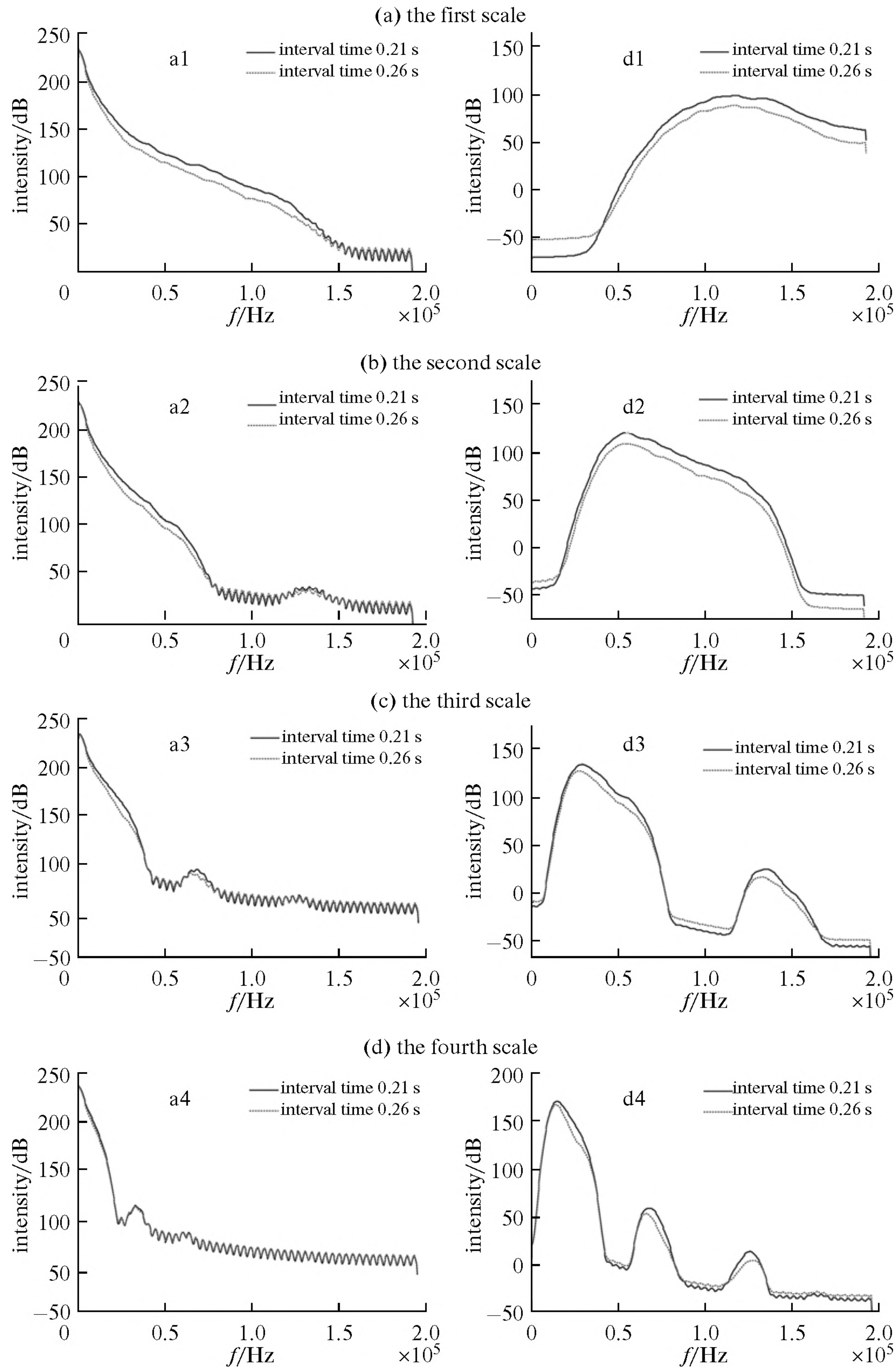

Fig. 7. Analyses with wavelet transform: (a) the first scale; (b) the second scale; (c) the third scale; (d) the fourth scale; (e) the fifth scale; (f) the sixth scale.

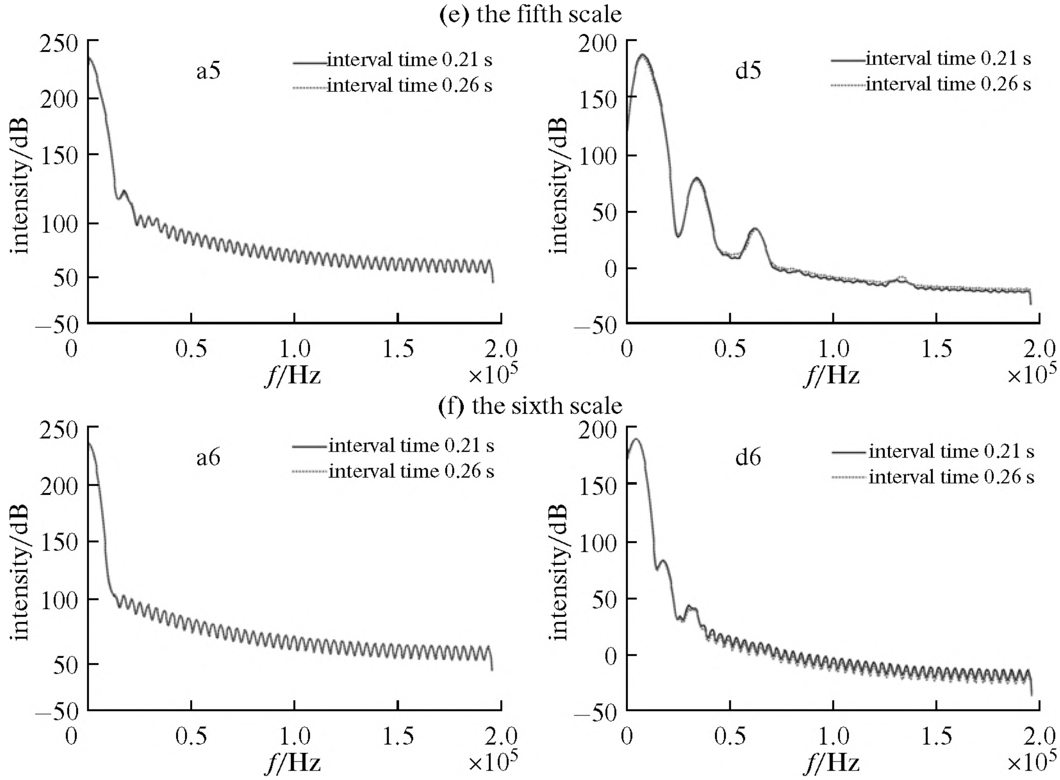

Fig. 7. (Contd.).

of explosions with different interval time spreads uniformly at low frequency range, unequally at high frequency range.

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