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Synthesis of Earthquake-Like Sound Using Seismic Ground-Motion Records

by Takashi Hirai and Nobuo Fukuwa

Abstract Listening to a sound representing ground motion is valuable to intuitively understand an earthquake, compared with conventional methods such as observing waveforms, Fourier spectra, and response spectra. In this study, we propose a new method for generating sound representing an earthquake, which has several differences in comparison with existing methods. In our new method, an earthquake-like sound is generated by modifying the frequency information of a generating function based on the symmetric Fourier analysis theory. Applying the method to existing seismograms illustrates three features of the sound generated by this method: the sound has the same duration as the seismogram, the sound pitch corresponds to the instantaneous frequency of the seismogram, and the sound volume corresponds to the envelope amplitude of the seismogram. Furthermore, we constructed a web-based earthquake-like sound generating system called Naion. Other applications will be implemented in the future.

Introduction

In general, seismic motion is expressed by time-series waveforms, Fourier spectra, response spectra, and so on. Although these expressions can scientifically and accurately explain the properties of seismic motion, understanding these properties is difficult for nonexperts. On the other hand, intuitive understanding of earthquakes and seismic motion is required for educational purposes in disaster mitigation. Appealing to the human senses is an effective method for this purpose.

One of the techniques to understand seismic motion through human senses is to experience it using a shaking table. This technique has been realized, for example, by Fukuwa *et al.* (2008), who developed a small shaking table for educational purposes, and by Fukuwa and Tobita (2008), who developed a shaking table that can simulate building responses. Furthermore, the National Research Institute for Earth Science and Disaster Prevention of Japan is operating the world's largest shaking table, E-Defense, in which full-scale structures can be tested for seismic motion.

Listening to a sound representing an earthquake is another technique to understand seismic motion with human senses. Although seismic motion and sound are both expressed as waveforms, there are distinct differences between them. Seismic motion mainly consists of frequency components below 10 Hz at most, whereas audible sound consists of frequency components from 20 Hz to 20 kHz. According to Hill *et al.* (1976) and Sylvander *et al.* (2007), elastic to acoustic transmission of *SV* waves for frequencies of a few tens of hertz gives a natural earthquake sound. However, the *SH* and surface waves, which produce the strongest shaking, are inaudible as any type of sound. Therefore, the waveform of a sound the same as that of seismic motion is almost inaudible. As a solution to this problem, compression along the time axis has been applied to seismograms in order to raise the frequency to the audible range (e.g., Dombois, 2002). Although this technique is simple, the duration of audible sound becomes much shorter than that of the original seismogram.

In this study, we propose a new method to synthesize sound representing an earthquake from an arbitrary seismic-motion record. Earthquake-like sounds generated by our method are required to have three features: (1) the sound must have the same duration as the seismogram, (2) the sound pitch must correspond to the instantaneous frequency of the seismogram, and (3) the sound volume must correspond to the envelope amplitude of the seismogram. In addition, we developed an earthquake-like sound generating system, Naion, on the web. Such an earthquake-like sound can be easily combined with video equipment because it has the same duration as the original seismogram.

Earthquake-Like Sound Synthesis Procedure

Symmetric Fourier Analysis

First, we briefly describe symmetric Fourier analysis, which provides the basic theory needed to synthesize an earthquake-like sound from a seismogram. In symmetric Fourier analysis, the amplitude and phase are defined in both the time and frequency domains. The fundamentals have been developed by Papoulis (1962); and, subsequently, Katukura *et al.* (1989), Katukura and Hayashi (1991), and others have theoretically and practically studied these fundamentals, which include application to seismic-motion records.

In this study, we denote a seismogram as $x(t)$ hereafter. Although $x(t)$ is defined in the range of $0 \le t < T$, here we redefine it in the range of $-T \le t < T$ with $x(t) = 0$ in $t < 0$. $x(t)$ is a time-domain causal real function. The Fourier transform of $x(t)$,

$$G(\omega) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t}dt, \quad (1)$$

is a frequency-domain complex conjugate function. Next, we define a new function

$$X(\omega) = U(\omega)\mathrm{Re}[G(\omega)], \quad (2)$$

in which $U(\omega)$ denotes a unit step function with respect to ω. $X(\omega)$ is a frequency-domain real causal function. The inverse Fourier transform of $X(\omega)$,

$$g(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} 4X(\omega)e^{i\omega t}d\omega, \quad (3)$$

is a time-domain complex conjugate function. The product between the real part of $g(t)$ and the unit step function equals the original seismogram $x(t)$,

$$x(t) = U(t)\mathrm{Re}[g(t)]. \quad (4)$$

The frequency-domain complex conjugate function $G(\omega)$ defined by equation (1) is known as the generating function of $X(\omega)$. $G(\omega)$ can be represented in polar form,

$$G(\omega) = A(\omega)e^{i\Phi(\omega)}, \quad (5)$$

in which $A(\omega)$ and $\Phi(\omega)$ denote the absolute value and the phase angle of $G(\omega)$, respectively. Although the absolute value $A(\omega)$ represents the contribution to $x(t)$, the derivative of the phase, $t_{\mathrm{gr}}(\omega) = d\Phi(\omega)/d\omega$, represents the group delay time of the frequency component ω.

On the other hand, the time-domain complex conjugate function $g(t)$ defined in equation (3) is called the generating function of $x(t)$, which represents a characteristic of $x(t)$. $g(t)$ can be written in polar form as

$$g(t) = a(t)e^{i\varphi(t)}. \quad (6)$$

Here, $a(t)$ and $\varphi(t)$ represent the envelope amplitude and the instantaneous value of the phase of $x(t)$, respectively. Therefore, the derivative of the phase $\omega_{\mathrm{gr}}(t) = d\varphi(t)/dt$ represents the instantaneous value of the angular frequency of $x(t)$. We call $f_{\mathrm{gr}}(t) = \omega_{\mathrm{gr}}(t)/2\pi$ the instantaneous frequency

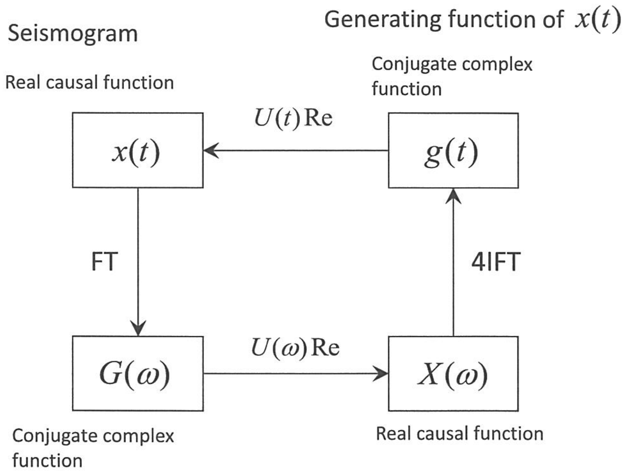

Figure 1. Schematic flow of symmetric Fourier analysis. (FT, Fourier transform; and 4IFT, four times inverse Fourier transform.)

hereafter. Figure 1 shows the schematic flow of symmetric Fourier analysis. According to Figure 1, there is a symmetric relation between time and frequency domains.

The phase angle $\varphi(t)$ is defined in the range $-\pi \le \varphi(t) < \pi$. In this study, the following algorithm is used to calculate the instantaneous angular frequency $\omega_{\mathrm{gr}}(t) = d\varphi(t)/dt$ in the discrete form:

$$\omega_{\mathrm{gr}.i} = \Delta\varphi_i/\Delta t \quad (7)$$

with

$$\Delta\varphi_i = \begin{cases} \varphi_{i+1} - \varphi_i & (\varphi_{i+1} - \varphi_i > -\pi) \\ \varphi_{i+1} - \varphi_i + 2\pi & (\varphi_{i+1} - \varphi_i \le -\pi) \end{cases}, \quad (8)$$

in which φ_i denotes the phase angle at time $i\Delta t$.

Sound Wave Synthesis Using a Generating Function

In the following description, variables related to the seismogram and those related to the earthquake-like sound are marked by superscripts E and S, respectively. The waveform of seismic motion consists of frequency components less than a few tens of hertz, whereas the audible frequency ranges from 20 Hz to 20 kHz. Therefore, we need to synthesize a waveform consisting of high-frequency components. In this study, we modify the instantaneous frequency of the time-domain generating function. Combining the envelope amplitude and the modified instantaneous frequency, a new generating function is derived as

$$g^{\mathrm{S}}(t) = a^{\mathrm{S}}(t)e^{i\varphi^{\mathrm{S}}(t)} \quad (9)$$

with

$$\varphi^{\mathrm{S}}(t) = \int_0^t \omega_{\mathrm{gr}}^{\mathrm{S}}(\tau)d\tau, \quad (10)$$

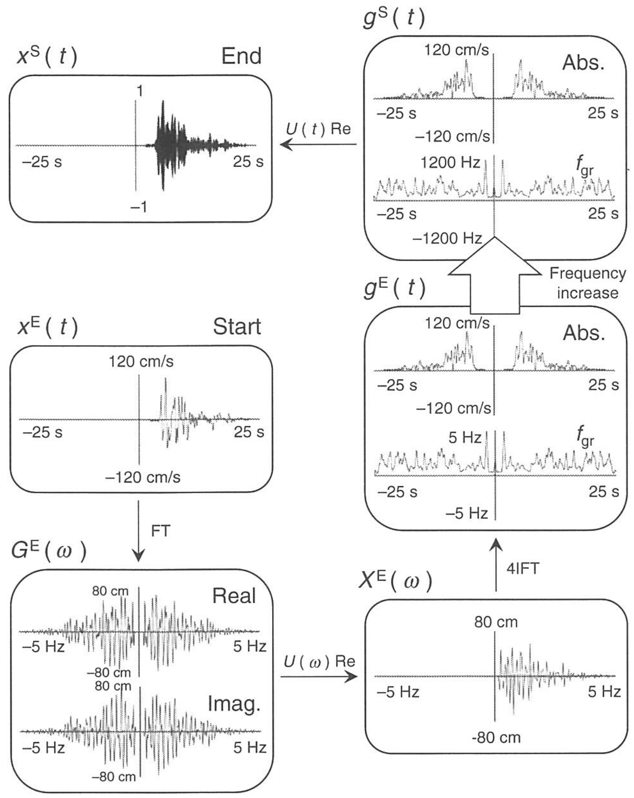

Figure 2. Flowchart of synthesis of earthquake-like sound. (Real, real part; Imag., imaginary part; and Abs., absolute value.)

$$a^{S}(t) = a^{E}(t), \tag{11}$$

and

$$\omega_{gr}^{S}(t) = k\omega_{gr}^{E}(t), \tag{12}$$

in which k denotes the scaling ratio of frequency from the seismic motion to the sound. Applying the third step of symmetric Fourier analysis to equation (9), a real causal function of the time domain that has audible frequency is derived. The above mentioned procedure is schematically shown in Figure 2.

Taking the instantaneous frequency of the ground-motion record flattens the spectrum: only the dominant frequency is conserved when calculating the derivative of the phase. The advantage of this method is the possibility of very simply modifying the frequency content of the seismogram to generate audible sounds. On the other hand, working on the instantaneous frequency causes monotonous sounds. This drawback is overcome by artificial high-frequency enrichment, which is described later.

Educational Tuning of Earthquake-Like Sound

The most fundamental procedure to synthesize earthquake-like sound is explained in the Sound Wave Synthesis Using a Generating Function section. In this section, we try to modify the details of the method in order to produce more realistic sound. The sound generated by the above method reflects the time changes in intensity and frequency of the seismogram; however, it does not sound earthquake-like. The most obvious reason is that the sound produced is monotonous, consisting of rising and falling pure tones, and requires modification for educational use.

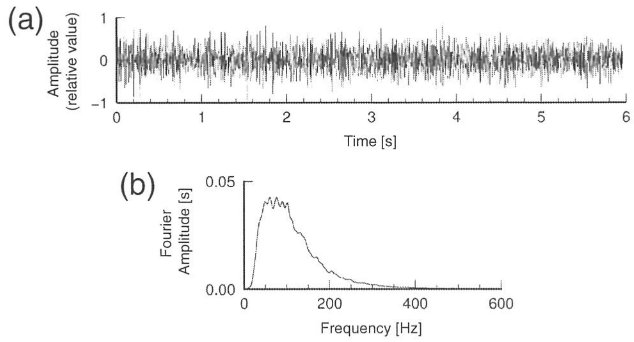

Figure 3. (a) Waveform of the timbre sample used to synthesize realistic earthquake-like sound; (b) the Fourier amplitude spectrum of the timbre sample.

Sound Pitch Tuning. Sound pitch depends on the logarithm of the frequency of a phonic wave: namely an octave of sound corresponds to a doubling in frequency. Although earthquake-like sound can be synthesized by the procedure described in the Sound Wave Synthesis Using a Generating Function section, its frequency range may be too wide. For example, assuming the frequency range of seismic motion to be from 0.1 to 10 Hz, that of the earthquake-like sound rises to 6.64 octaves. One of the solutions is a logarithmic correspondence between the frequency of seismic motion and the earthquake-like sound. This is formulated as follows:

$$\log_2 \omega_{gr}^{S}(t) = \log_{\beta} \omega_{gr}^{E}(t) + \log_2 \omega_0^{S}, \tag{13}$$

in which β denotes the coefficient corresponding to one octave of earthquake-like sound and $\omega_0^{S}(= 2\pi f_0^{S})$ represents the sound frequency corresponding to 1 Hz of seismic motion. To apply sound pitch tuning, equation (12) is replaced by equation (13).

Sound Timbre Tuning. Sound timbre depends on the ratio of higher harmonics of a phonic wave. An earthquake-like sound generated using equation (9) has sine wave as a transmitting wave. A sound with a realistic timbre can be synthesized using a sound sample with a realistic timbre as a transmitting wave instead of a sine wave. Figure 3 shows an example of a realistic timbre sample and its Fourier spectrum, which is the sound of a ground rumble extracted from a commercially available CD of sound effects.

The duration of the sound sample shown in Figure 3 is only 6 s. However, considering this waveform is repeated many times, the sound sample is expressed as the form of the Fourier series:

$$h(t) = \sum_{n=-\infty}^{\infty} C_n e^{in\omega_0 t}, \tag{14}$$

in which C_n and ω_0 denote the complex Fourier coefficient of nth order higher harmonics and the fundamental angular frequency, respectively. From equation (14), the realistic sound $h(t)$ is synthesized by compiling many frequencies of sine waves. By analogy with equation (14), and by compiling equation (9) with weighting factors C_n for nth frequency, the generating function of the earthquake-like sound is synthesized as

$$g^{\mathrm{S}}(t) = \sum_{n=-\infty}^{\infty} C_n a^{\mathrm{S}}(t) e^{in\frac{\varphi^{\mathrm{S}}(t)}{\lambda}} = a^{\mathrm{S}}(t) h\left[\frac{\varphi^{\mathrm{S}}(t)}{\omega_1}\right] \tag{15}$$

with

$$\omega_1 = \lambda\omega_0. \tag{16}$$

The parameter λ in equation (15) is introduced to associate $e^{in\omega_0 t}$ in equation (14) and $e^{i\varphi^{\mathrm{S}}(t)}$ in equation (9) with reference to a certain frequency. For the synthesis of a realistic earthquake-like sound, equation (9) is replaced by equation (15), and $\varphi^{\mathrm{S}}(t)$ is calculated using equation (10) and substituting equation (12) or equation (13) in equation (10) in the integral of the angular frequency. Equation (15) can be interpreted to indicate that a realistic earthquake-like sound consists of an envelope amplitude that is identical to the corresponding seismic motion and a transmitting wave playing with a variable phase increasing rate, which has realistic timbre. In the case of $\omega_{\mathrm{gr}}^{\mathrm{S}}(t) = \omega_1$, a realistic timbre sample plays with its original speed.

Sound Volume Tuning. In the Sound Wave Synthesis Using a Generating Function section the envelope amplitude used for the earthquake-like sound is the same as that of the seismic motion. It guarantees a correspondence relation between the instantaneous amplitude of seismic motion and the earthquake-like sound. However, such a correspondence relation may cause an unnatural impression for the sound of long-period seismic motion. For example, the envelope amplitude is almost constant for a coda wave consisting of a surface wave generated by the resonance of a thick sedimentary basin. Earthquake-like sounds for such seismic motion also have a constant volume over a long time. In order to synthesize realistic sound, we use the absolute value of seismic motion instead of the envelope amplitude:

$$a^{\mathrm{S}}(t) = |x^{\mathrm{E}}(t)|. \tag{17}$$

Using equation (17), a sound with an amplitude proportional to the instantaneous amplitude of seismic motion can be synthesized.

Application to Real Seismograms and the Web-Based System

In this section, we apply our new method for synthesizing earthquake-like sound to two real seismograms. The first is the strong ground motion record observed at the Kobe Marine Observatory of the Japan Meteorological Agency in the 1995 Hyogoken-Nanbu earthquake (M 7.3). Because it was an inland earthquake and occurred in Kobe City, the seismogram consists of an intensive short-period component. The second is the strong ground motion record observed at the TKY007 station of K-NET, which is the strong ground motion observation network of the National Research Institute for Earth Science and Disaster Prevention of Japan, in the 2011 Tohoku earthquake. The station is 400 km from the earthquake hypocenter and is located on the Kanto sedimentary basin; thus, the seismic motion mainly consists of a long-period component. We call these two seismic-motion records the "Kobe wave" and the "Tohoku wave," respectively. To establish a correspondence between the sound volume and the kinetic energy of ground motion, earthquake-like sounds were generated on the basis of velocity waveforms converted from these acceleration records. They are openly available on the web with several other earthquake-like sounds. On listening to the generated sounds, the three features described in the Introduction section are confirmed: the earthquake-like sound has the same duration as the seismogram, the sound pitch corresponds to the instantaneous frequency of the seismic motion, and the sound volume corresponds to the envelope amplitude or instantaneous amplitude of the seismogram.

In addition, we developed the web-based system Naion in which an earthquake-like sound is generated from an arbitrary seismogram. Figure 4 shows the top page of Naion. Users can adjust the pitch and timbre of the earthquake-like sound.

Earthquake-Like Sound for the Kobe Wave

Three types of earthquake-like sounds were generated by applying our method to the Kobe wave. The parameters used to synthesize the earthquake-like sounds are listed in Table 1. Figure 5 shows the ground-motion record and the three types of earthquake-like sounds of the Kobe wave. Although the original ground-motion record is given as an acceleration record, we use the velocity waveform to produce the earthquake-like sound in this study. Figure 6 shows the instantaneous frequency of the ground-motion record and the earthquake-like sound of the Kobe wave.

First, we consider the most elemental case, earthquake-like sound A. According to Figure 5, the ground-motion record and earthquake-like sound A have the same duration. The volume of sound A varies with time corresponding to the energy of the ground motion, because its envelope of sound varies with time corresponding to that of the ground-motion record. According to Figure 6, the instantaneous

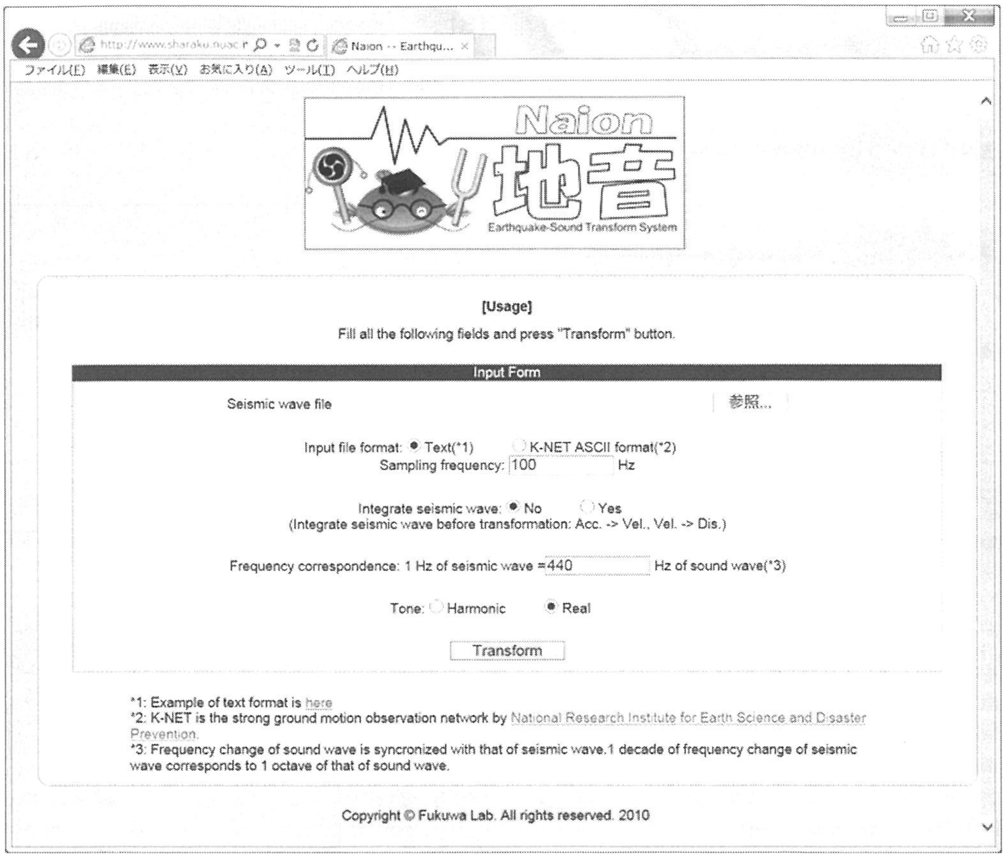

Figure 4. The top page of the web-based earthquake-like sound generating system Naion.

frequency of earthquake-like sound A proportionally varies with time corresponding to that of the ground-motion record. From the above results, three features of the earthquake-like sound are confirmed: the earthquake-like sound generated by our method has the same duration as the seismogram, the sound pitch corresponds to the instantaneous frequency of the seismogram, and the sound volume corresponds to the envelope amplitude of the seismogram.

Second, we consider the realistic case, earthquake-like sound B. According to Figure 6, sound A has a pitch range from 70 Hz to 660 Hz, that is, 3.2 octaves. On the other hand, sound B has a pitch range from 220 to 440 Hz (1.0 octaves). The difference in sound pitch between A and B is the result of tuning in the instantaneous frequency increase. Figure 7 shows an enlargement of earthquake-like sounds A and B. According to Figure 7, sound B has a nonsteady waveform, whereas sound A has a harmonic waveform. This is the result of tuning in the transmitting wave. In the case of sound B, although the instantaneous frequency corresponds to that of the seismogram, the different frequency components are mixed in order to modify the timbre. Therefore, the correspondence of the instantaneous frequency between the seismogram and the earthquake-like sound is not physically rigorous.

Finally, earthquake-like sound C has a different envelope than those of A and B. According to Figure 5, the volume change in sound C is more variable than in sounds A and B. The physical meaning indicates that the sound volume of A and B corresponds to the envelope amplitude of the ground motion, whereas the sound volume of C corresponds to the instantaneous velocity of the ground motion.

Discussion of Sound Timbre Tuning. In this subsection, we discuss the effect of sound timbre tuning. Figure 8 shows the sound waveform of the Kobe wave, velocity envelope of

Table 1
Parameters Used to Synthesize Earthquake-Like Sounds

	Frequency Scaling	Timbre	Envelope
A	Linear equation (12) $k = 220$	Monotonous equation (9)	Envelope equation (11)
B	Logarithmic equation (13) $f_0 = 310$ Hz, $\beta = 10$	Realistic equation (15) $\omega_1 = 1382\ \text{s}^{-1}$	Envelope equation (11)
C	Logarithmic equation (13) $f_0 = 310$Hz, $\beta = 10$	Realistic equation (15) $\omega_1 = 1382\ \text{s}^{-1}$	Velocity equation (17)

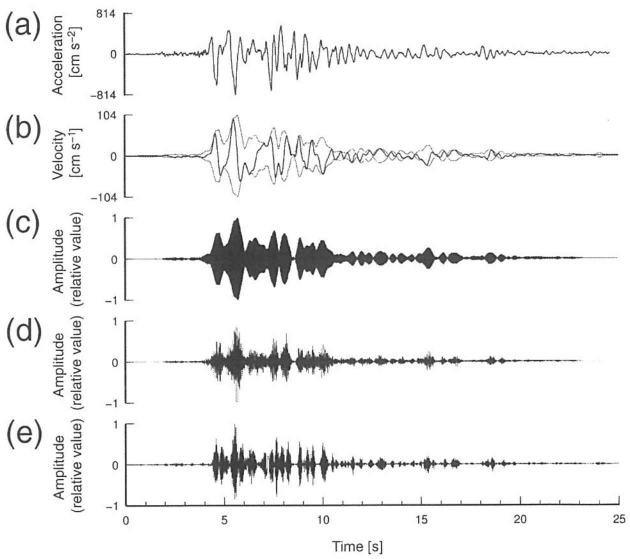

Figure 5. (a) Acceleration waveform of the Kobe wave; (b) velocity waveform of the Kobe wave (thick line) and its envelope (thin line); (c) sound waveform without any tuning (sound A); (d) sound waveform with realistic timbre sample (sound B); and (e) sound waveform with realistic timbre sample and velocity-based envelope (sound C).

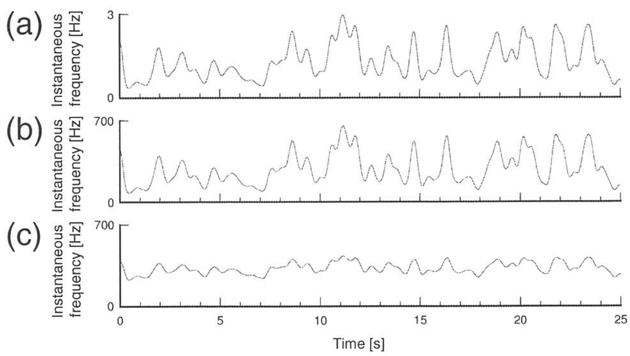

Figure 6. (a) Instantaneous frequency of the Kobe wave; (b) instantaneous frequency of the earthquake sound without any tuning (sound A); and (c) instantaneous frequency of the earthquake sound with timbre tuning (sound B).

ground motion, instantaneous frequency of the sound, and nonstationary Fourier amplitude spectrum of the sound for every second. In this subsection, the earthquake-like sound is generated using linear frequency scaling (equation 12), a realistic timbre sample (equation 15), and an envelope proportional to that of ground motion (equation 11).

According to Figure 8, the nonstationary spectrum consists of a frequency component with a very broad range, causing a variegated sound. The greater the velocity envelope, the higher the level of the nonstationary spectrum. In addition, when the instantaneous frequency is high, the distribution of the nonstationary spectrum spreads to the high-frequency region. The time range of the nonstationary

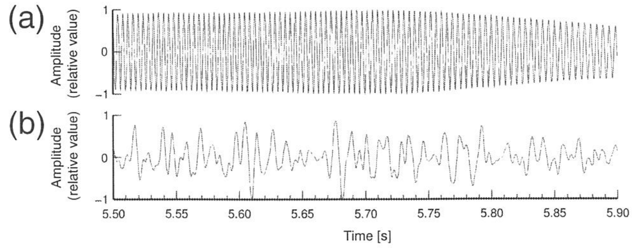

Figure 7. Enlargement of (a) the sound waveform without any tuning (sound A) and (b) the sound waveform with a realistic timbre sample (sound B) from 5.5 to 5.9 s.

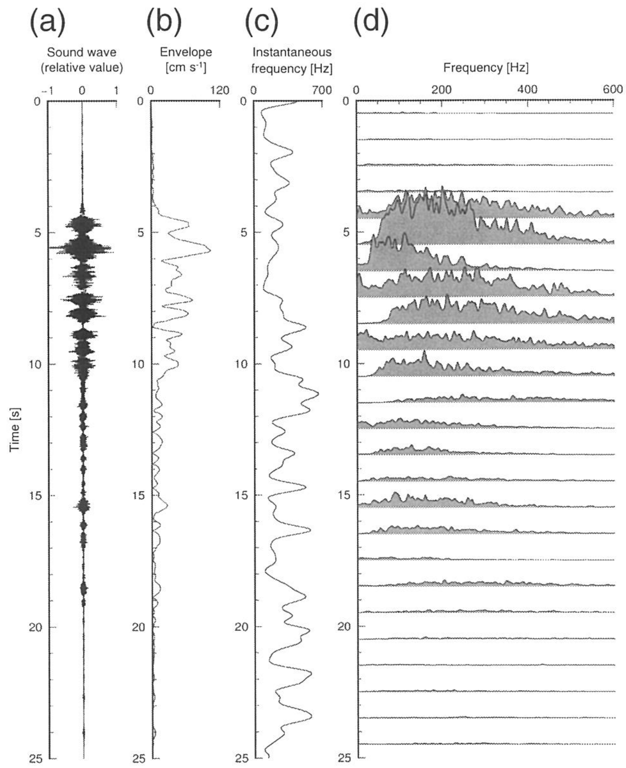

Figure 8. (a) Sound waveform of the Kobe wave with realistic timbre sample; (b) velocity envelope of the Kobe wave; (c) instantaneous frequency of the sound of the Kobe wave; and (d) nonstatic Fourier amplitude spectrum of the sound of the Kobe wave.

spectrum shown in Figure 8 is 1 s, whereas the timbre sample shown in Figure 3 has a duration of 6 s. Thus, each spectrum shown in Figure 8 does not reflect all the characteristics of the timbre sample; nevertheless, each spectrum seems to have a shape approximately similar to that of Figure 3b, with vertical and horizontal scaling corresponding to the velocity envelope and instantaneous frequency, respectively.

Robustness of the Method with Respect to Noise. In general, a strong ground motion record includes some noise. In this subsection, we discuss the robustness of the method with respect to noise. Figure 9 shows the acceleration, velocity,

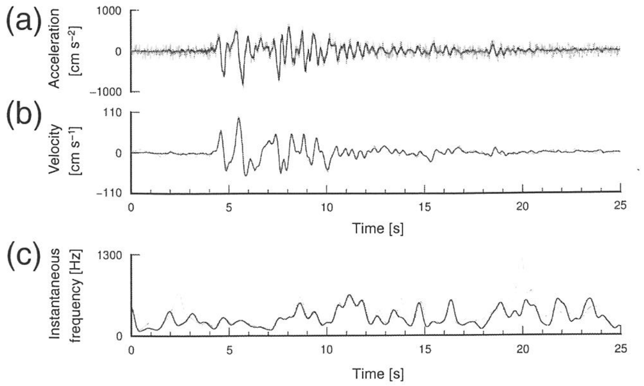

Figure 9. (a) Acceleration waveform of the Kobe wave without noise (black line) and with noise (gray line); (b) velocity waveform of the Kobe wave without noise (black line) and with noise (gray line); and (c) instantaneous frequency of earthquake-like sound of the Kobe wave without noise (black line) and with noise (gray line).

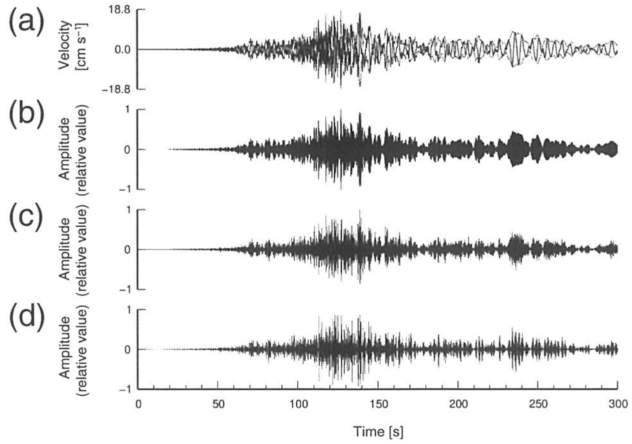

Figure 10. (a) Velocity waveform of the Tohoku wave (thick line) and its envelope (thin line); (b) sound waveform without any tuning (sound A); (c) sound waveform with realistic timbre sample (sound B); and (d) sound waveform with realistic sample and velocity-based envelope (sound C).

and instantaneous frequency of the earthquake-like sound without and with noise. Frequency scaling is conducted in the same manner as for sound A in Table 1. The noise is given to the acceleration as a random number according to the normal distribution with a standard deviation of 100 cm s^{-2}. This is very large for accelerometer noise; nevertheless, the instantaneous frequency of the earthquake-like sound is calculated almost correctly, except in the section with a small signal-to-noise ratio. Therefore, the method produced in this study has sufficient robustness with respect to noise, until it is comparable in amplitude to the signal.

Earthquake-Like Sound for the Tohoku Wave

Three types of earthquake-like sounds were generated by applying our method to the Tohoku wave with the parameters listed in Table 1. Figure 10 shows the ground-motion record and the earthquake-like sounds of type A, B, and C. For earthquake-like sounds A and B, the same discussion as described in the Earthquake-Like Sound for the Kobe Wave section applies. However, in some portions of the sound A and B signals, the sound does not change for a few seconds. This is due to the slow fluctuation of the envelope and the instantaneous frequency of the ground motion. Therefore, the slow fluctuation of the sound volume and the sound pitch indicate that the envelope amplitude and the instantaneous frequency of the ground motion do not change over a long time. Earthquake-like sound C is produced in the same manner as in the case of the Kobe wave. However, for educational purposes using video equipment of the ground motion, sound C is considered to be easier to understand for nonexperts.

Conclusion

We developed a new method to synthesize earthquake-like sounds from seismograms using the symmetric Fourier analysis theory. In the method, an earthquake-like sound is generated by combining the envelope amplitude of the original seismogram and the instantaneous frequency extended to audible range. Additional tuning of the sound pitch, sound timbre, and the time series of the envelope amplitude are available to synthesize a more realistic sound. Some examples of earthquake-like sounds are openly available on our website. Furthermore, we developed the web-based earthquake-like sound generating system, Naion, in which an arbitrary seismogram can be automatically transformed to a corresponding earthquake-like sound. By combining the earthquake-like sound generating program with video equipment, an audiovisual earthquake experience system with synchronized earthquake-like sound can be constructed. Other applications will be implemented in the future.

Data and Resources

The seismogram of the 1995 Hyogoken-Nanbu earthquake can be obtained from Japan Meteorological Business Support Center at http://www.jmbsc.or.jp/english/index-e.html (last accessed February 2014). The seismogram of the 2011 Tohoku earthquake can be obtained from National Research Institute for Earth Science and Disaster Prevention of Japan at http://www.bosai.go.jp/e/ (last accessed October 2013). Some figures were made using the Generic Mapping Tools (http://gmt.soest.hawaii.edu/; Wessel and Smith, 1995). Some examples of the earthquake-like sounds are openly available at http://www.sharaku.nuac.nagoya-u.ac.jp/etaiken/staiken_en.html (last accessed February 2014). The earthquake-like sound generating system Naion is openly available at http://www.sharaku.nuac.nagoya-u.ac.jp/naion/en/ (last accessed February 2014).

Acknowledgments

We used the acceleration record observed at the Kobe Marine Observatory by the Japan Meteorological Agency and K-NET by the National Research Institute for Earth Science and Disaster Prevention of Japan. Kazumi Kurata of Nagoya University Disaster Mitigation Research Center helped us in developing the web-based earthquake-like sound generating system Naion. We are grateful to two reviewers and the editors for giving us helpful comments. We would like to thank Enago for the English language review.

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Graduate School of Environmental Studies
Nagoya University
Furo-cho
Chikusa-ku
Nagoya 464-8601, Japan
hirai@sharaku.nuac.nagoya-u.ac.jp
(T.H.)

Disaster Mitigation Research Center
Nagoya University
Furo-cho
Chikusa-ku
Nagoya 464-8601, Japan
fukuwa@sharaku.nuac.nagoya-u.ac.jp
(N.F.)

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