Synthesis of Earthquake Sound Using Seismic Motion Record and its Application to Audiovisual Earthquake Experience System

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SUMMARY
Listening to a sound representing ground motion is valuable to understand an earthquake intuitively compared with seeing waveform, Fourier spectrum, response spectrum, and so on. In this study, we propose a new method to make an earthquake sound, in which several rules different from existing methods are used. In our new method, an earthquake sound is generated by modifying the frequency information of generating function based on the theory of symmetric Fourier analysis. Applying the method to existing seismograms, three features of the sound generated by this method are confirmed: the sound has same duration time with the seismogram, sound pitch corresponds to instantaneous frequency of seismogram, and sound volume corresponds to envelope amplitude of seismogram. Furthermore, we constructed the Web-based earthquake sound generating system "Naion" and the audiovisual earthquake experience system "EVEREST" combining with video equipment. Other applications would be implemented hereafter.

Keywords: Earthquake Sound, Audiovisual Earthquake Experience System, Symmetric Fourier Analysis

1. INTRODUCTION

In general, a seismic motion is expressed by time series waveform, Fourier spectrum, response spectrum, and so on. Although these expressions can explain the property of seismic motion scientifically and correctly, it is difficult for non-expert people to understand the property of seismic motion. On the other hand, intuitive understanding of earthquake and seismic motion is required in education for disaster prevention. Appealing to human senses is one of effective ways for this purpose.

One of the ways to understand seismic motion by human sense is to experience it using shaking table. This way already has been realised. For example, Hanai *et al.* (2009) developed a small shaking table for education, Fukuwa *et al.* (2007) developed a shaking table which can simulate building response. Furthermore, 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.

On the other hand, hearing a sound representing an earthquake is also one of the ways to understand seismic motion by human sense. Although seismic motion is expressed by a waveform as with a sound, there is decisive difference between these two waves. While seismic motion consists of frequency component under 10 Hz at most, hearable sound consists of frequency component of from 20 Hz to 20 kHz. Therefore, a sound whose waveform is same to seismic motion is not hearble. As a solution for this problem, compression along time axis has been applied to seismogram in order to raise frequency to hearable range (e.g. Dombois, 2002; U.S. Geological Survey, 2009). Although this method is simple, duration time of hearable sound becomes much shorter than original seismogram.

In this study, we propose a new method to synthesise an earthquake sound from arbitrary seismic motion record. Earthquake sound generated by our method is required to have three features: the sound must have same duration time with the seismogram, sound pitch must correspond to instantaneous frequency of seismogram, and sound volume must correspond to envelope amplitude of seismogram. In addition, we developed the earthquake sound generating system working on the Web named "Naion." Such an earthquake sound can be combined with video equipment easily since it has same duration time with original seismogram. We also developed an audiovisual earthquake experience system "EVEREST." Since all of the products can not be shown in this paper, refer to our Web Page (http://www.sharaku.nuac.nagoya-u.ac.jp/) for more detail information.

2. SYNTHESIS PROCEDURE OF EARTHQUAKE SOUND

2.1. Symmetric Fourier analysis

First, we briefly describe the technique of symmetric Fourier analysis, which is the basic theory to synthesise an earthquake sound from a seismogram. In the symmetric Fourier analysis, the amplitude and phase is defined not only in time domain but also in frequency domain. It has developed by Papoulis (1962) in basement, consequently Izumi and Katsukura (1983), Izumi et al. (1988), Katsukura et al. (1989), and so on, have studied theoretically and practically, including application for seismic motion records.

We denote an seismogram $x(t)$ 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 $x(t)$,

$$G(\omega) = \int_{-\infty}^{\infty} x(t) e^{-i\omega t} dt, \tag{2.1}$$

is a frequency-domain complex conjugate function. Real and imaginary parts of $G(\omega)$ form a relation of Hilbert transform pair, that is,

$$\mathrm{Im}[G(\omega)] = -\frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\mathrm{Re}[G(\zeta)]}{\omega - \zeta} d\zeta \quad \text{and} \tag{2.2}$$

$$\mathrm{Re}[G(\omega)] = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\mathrm{Im}[G(\zeta)]}{\omega - \zeta} d\zeta + C. \tag{2.3}$$

Here, integral is selected as Cauchy's main value. C is necessary when $x(t)$ has a singular point at the origin, but in this case, we can consider $C = 0$ since $x(t)$ does not have any singular point. Next we define a new function

$$X(\omega) = U(\omega)\,\mathrm{Re}[G(\omega)], \tag{2.4}$$

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

$$g(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} 4X(\omega) e^{i\omega t} d\omega, \tag{2.5}$$

is time-domain complex conjugate function. Real and imaginary parts of $g(t)$ form a relation of Hilbert transform pair. It is known that the product between real part of $g(t)$ and unit step function equals to the original seismogram $x(t)$,

$$x(t) = U(t)\,\mathrm{Re}[g(t)]. \tag{2.6}$$

Frequency-domain complex conjugate function $G(\omega)$ defined by Eqn (2.1) is known as the generating function of $X(\omega)$. $G(\omega)$ can represented in polar form,

$$G(\omega) = A(\omega)e^{i\Phi(\omega)} \tag{2.7}$$

with

$$A(\omega) = \sqrt{[G_{\mathrm{re}}(\omega)]^2 + [G_{\mathrm{im}}(\omega)]^2} \quad \text{and} \tag{2.8}$$
$$\Phi(\omega) = \tan^{-1}[G_{\mathrm{im}}(\omega)/G_{\mathrm{re}}(\omega)], \tag{2.9}$$

where $G_{\mathrm{re}}(\omega)$ and $G_{\mathrm{im}}(\omega)$ denote real and imaginary part of $G(\omega)$, respectively. While the absolute value $A(\omega)$ represents the contribution to $x(t)$, the derivative of phase, $t_{\mathrm{gr}}(\omega) = d\Phi(\omega)/d\omega$, represents the group delay time of frequency component ω.

On the other hand, the time-domain complex conjugate function $g(t)$ defined as Eqn (2.5) is called the generating function of $x(t)$, which represents the characteristic of $x(t)$. $g(t)$ can be written in polar form as

$$g(t) = \alpha(t)e^{i\varphi(t)} \tag{2.10}$$

with

$$\alpha(t) = \sqrt{[g_{\mathrm{re}}(t)]^2 + [g_{\mathrm{im}}(t)]^2} \quad \text{and} \tag{2.11}$$
$$\varphi(t) = \tan^{-1}[g_{\mathrm{im}}(t)/g_{\mathrm{re}}(t)], \tag{2.12}$$

where $g_{\mathrm{re}}(t)$ and $g_{\mathrm{im}}(t)$ denote the real and imaginary part of $g(t)$, respectively. Here $\alpha(t)$ and $\varphi(t)$ represent the envelope and the instantaneous value of phase of $x(t)$, respectively. Therefore, the derivative of the phase, $\omega_{\mathrm{gr}}(t) = d\varphi(t)/dt$, means the instantaneous value of angular frequency of $x(t)$. We call $f_{\mathrm{gr}}(t) = \omega_{\mathrm{gr}}(t)/2\pi$ instantaneous frequency hereafter. Fig. 2.1 shows the schematic flow of symmetric Fourier analysis. According to Fig. 2.1, there is a symmetric relation between time domain and frequency domain.

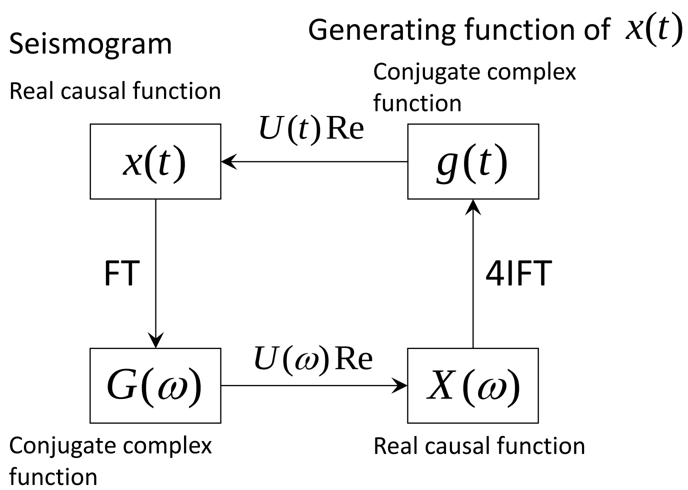


Figure 2.1. Schematic flow of symmetric Fourier analysis. “FT” and “IFT” mean Fourier transform and inverse Fourier transform, respectively.

2.2. Synthesis of sound wave using generating function

In following description, the variables related to the seismogram and those related to the earthquake sound are remarked by upper subscript “E” and “S”, respectively. The waveform of seismic motion consists of frequency component about less than 10 Hz, while hearable frequency range is from 20 Hz to 20 kHz. So that we should synthesise the waveform consisting of high frequency components. In this study, we modify the instantaneous frequency of time domain generating function. Combining envelope amplitude same to Eqn (2.11) and modified instantaneous frequency, a new generating function is derived as

$$g^{\mathrm{S}}(t) = \alpha^{\mathrm{S}}(t) e^{i\varphi^{\mathrm{S}}(t)} \tag{2.13}$$

with

$$\varphi^{\mathrm{S}}(t) = \int_0^t \omega_{\mathrm{gr}}^{\mathrm{S}}(\tau) d\tau\,, \tag{2.14}$$

$$\alpha^{\mathrm{S}}(t) = \alpha^{\mathrm{E}}(t) \quad \text{and} \tag{2.15}$$

$$\omega_{\mathrm{gr}}^{\mathrm{S}}(t) = k\omega_{\mathrm{gr}}^{\mathrm{E}}(t)\,, \tag{2.16}$$

where k means the amplifying ratio of frequency from the seismic motion to the sound. Applying the third step of symmetric Fourier analysis to Eqn (2.13), a real causal function of time domain which has hearable frequency is derived. Above mentioned procedure is shown in Fig. 2.2 schematically.

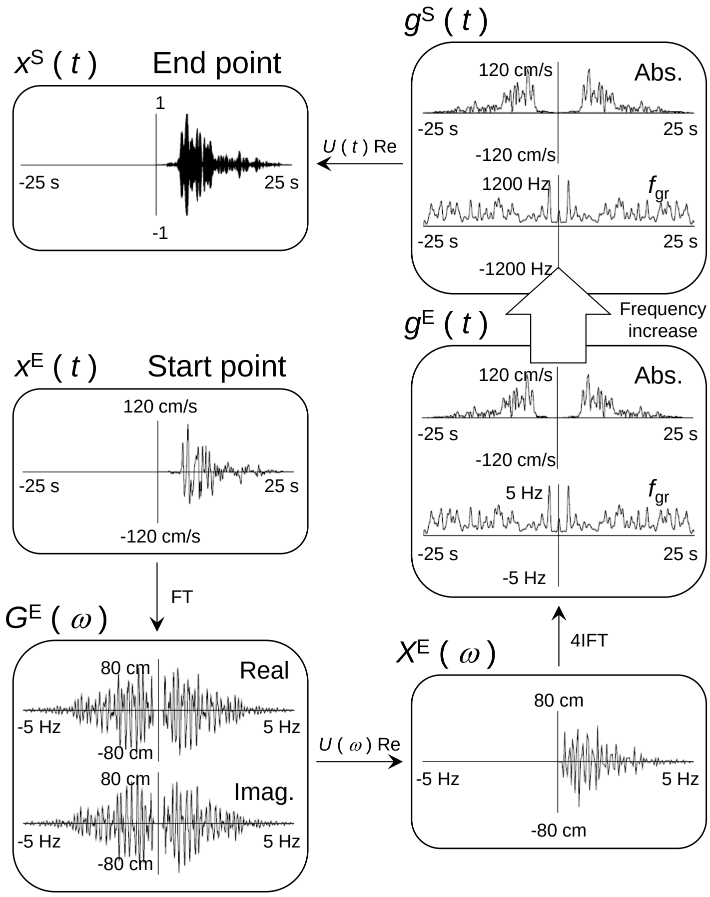


Figure 2.2. Flowchart of synthesis of earthquake sound waveform. “Real”, “Imag.” and “Abs.” mean real part, imaginary part and absolute value, respectively.

2.3. Educational tuning of earthquake sound

The most fundamental procedure to synthesise earthquake sound is explained in Section 2.2. In this section, we try to modify the details of method in order to make more realistic sound. Hearable sound has three important properties, namely, pitch, tone and volume. Each property corresponds to frequency, mixing ratio of higher harmonics and envelope amplitude of sound waveform, respectively. Following descriptions remark these three characteristics of sound waveform.

2.3.1. Tuning of sound pitch

Sound pitch depends on the logarithm of frequency of phonic wave, namely an octave of sound corresponds to a twice of frequency. Although an earthquake sound can be synthesised by the procedure in Section 2.2, its frequency range seems to be too wide. For example, assuming the frequency range of seismic motion is from 0.1 to 10 Hz, that of earthquake sound rises to 6.64 octaves. One of the solutions is logarithmic correspondence between frequency of seismic motion and earthquake sound. This is formulised as follows:

$$\log_2 f_{\mathrm{gr}}^{\mathrm{S}}(t) = \log_\beta f_{\mathrm{gr}}^{\mathrm{E}}(t) + \log_2 f_0^{\mathrm{S}}, \tag{2.17}$$

where β denotes the coefficient corresponding to one octave of earthquake sound, f_0^{S} denotes the sound frequency corresponding to 1 Hz of seismic motion.

2.3.2. Tuning of sound tone

Sound tone depends on the ratio of higher harmonics of phonic wave. An earthquake sound generated using Eqn (2.13) has sine wave as a transmitting wave. A sound which has realistic tone can be synthesised using a sound sample of realistic tone as transmitting wave instead of sine wave. Waveform of realistic tone sample can be written in the form of Fourier integral:

$$h(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H(\omega) e^{i\omega t} d\omega, \tag{2.18}$$

where $h(t)$ and $H(\omega)$ denote realistic tone sample and its Fourier transform. Using Eqn (2.18) as transmitting wave instead of complex exponential function, generating function of earthquake sound is synthesised as

$$g^{\mathrm{S}}(t) = \alpha^{\mathrm{S}}(t)\int_{-\infty}^{\infty} H(n\omega_1) e^{in\varphi^{\mathrm{S}}(t)} dn = \frac{2\pi}{\omega_1}\alpha^{\mathrm{S}}(t) h\left[\frac{\varphi^{\mathrm{S}}(t)}{\omega_1}\right], \tag{2.19}$$

where ω_1 is a reference frequency. Eqn (2.19) can be interpreted that a realistic earthquake sound consists of an envelope amplitude same to corresponding seismic motion and transmitting wave playing with variable phase increasing rate, which has realistic tone. In the case of $\omega_{\mathrm{gr}}^{\mathrm{S}}(t) = \omega_1$, realistic tone sample plays with its original speed.

2.3.3. Tuning of sound volume

In Section 2.2, envelope amplitude used in earthquake sound is same to that of seismic motion. It guarantees the correspondence relation between the instantaneous amplitude of seismic motion and earthquake sound. However, such correspondence relation may cause unnatural impression for the sound of long-period seismic motion. For example, envelope amplitude is almost constant for coda wave consisting of surface wave generated by resonance of thick sedimentary basin. Earthquake sound for such seismic motion also has constant volume during long time. In order to synthesise realistic sound, we use the absolute value of seismic motion instead of envelope amplitude:

$$\alpha^{S}(t) = \left| x^{E}(t) \right| . \qquad (2.20)$$

Using Eqn (2.20), a sound whose amplitude is proportional to instantaneous amplitude of seismic motion can be synthesised.

3. APPLICATION TO REAL SEISMOGRAMS AND WEB-BASED SYSTEM

In this section, we apply our new method to synthesise earthquake sound to two real seismograms. The first is the strong ground motion record observed at Kobe Marine Observatory of Japan Meteorological Agency in the 1995 Hyogoken-Nambu Earthquake (*M* 7.3). Since it was inland earthquake and occurred near Kobe City, the seismogram consists of intensive short-period component. The second is the strong ground motion record observed at TKY007 station of K-NET, which is the strong ground motion observation network by National Research Institute for Earth Science and Disaster Prevention of Japan, in the 2011 off the Pacific coast of Tohoku Earthquake. Besides the distance from hypocentre of the earthquake rises to 400 km, the station is on Kanto sedimentary basin. So that the seismic motion mainly consists of long-period component. Earthquake sounds were generated based on velocity waveforms converted from these accelograms. They are opened on the Web with other several earthquake sounds (http://www.sharaku.nuac.nagoya-u.ac.jp/etaiken/staiken_en.html). Hearing them, three features described in Section 1 are confirmed: the earthquake sound has same duration time with the seismogram, the sound pitch corresponds to instantaneous frequency of seismic motion, and sound volume corresponds to envelope amplitude or instantaneous amplitude of seismogram.

In addition, we developed a Web-based system named "Naion" in which an earthquake sound is generated from arbitrary seismogram (http://www.sharaku.nuac.nagoya-u.ac.jp/naion/en/). Fig. 3.1 shows the top page of "Naion." Users can adjust pitch and tone of earthquake sound.

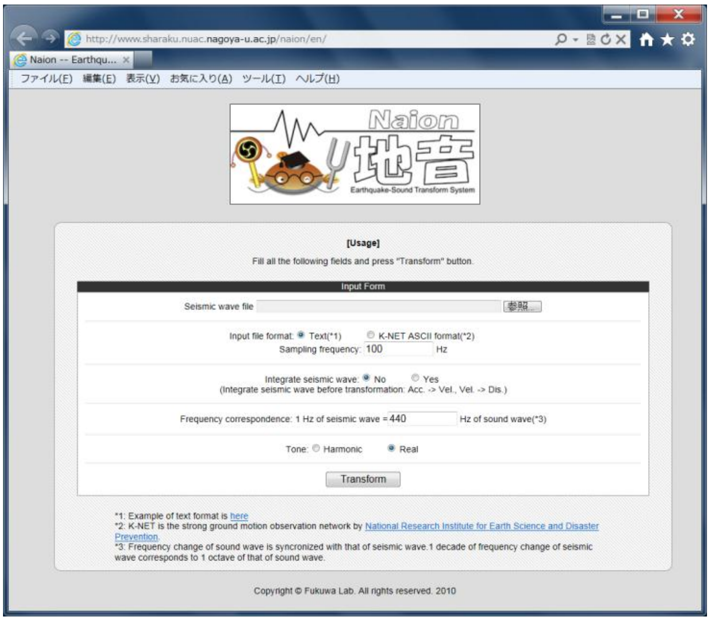
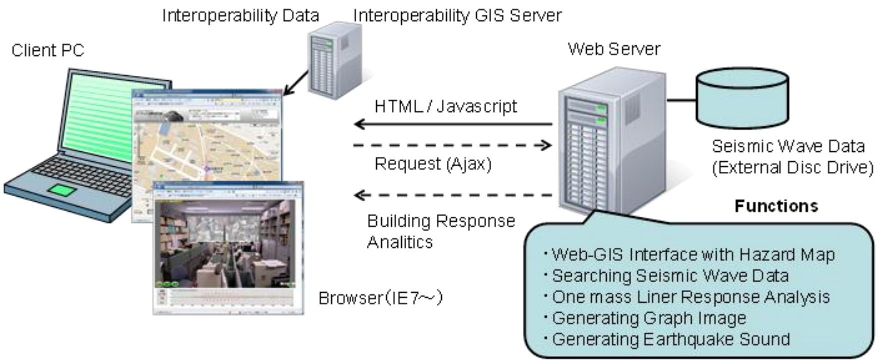


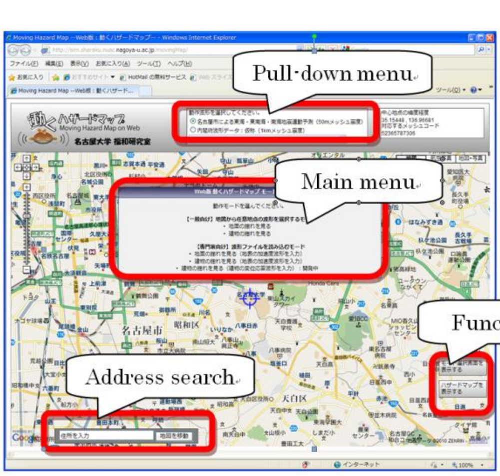
Figure 3.1. Top page of Web-based earthquake sound generating system "Naion."

4. AUDIOVISUAL EARTHQUAKE EXPERIENCE SYSTEM

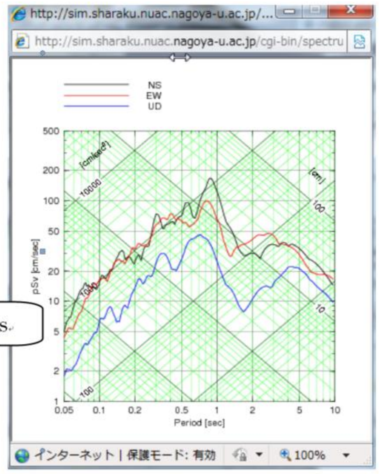
We developed the virtual earthquake response experience system "EVEREST" applying the earthquake sound generating program. Whole system diagram is shown in Fig. 4.1 (a). Main components as strong ground motion record of each geographic grid, structure response calculating



(a) Whole system of “EVEREST”



(b) Main view (Web-GIS Interface)



(c) Pseudo velocity response spectrum

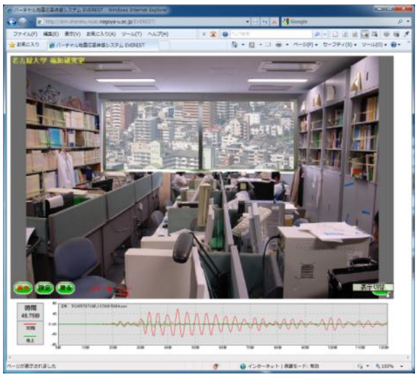
Figure 4.1. Whole system of “EVEREST” and operation windows.

module, and graph drawing module are installed in Web server. Users can access the system using a personal computer through the Web.

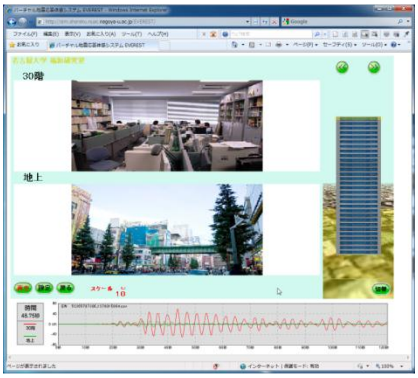
Main view of the system is shown in Fig. 4.1 (b). Web-GIS interface of main view is composed with Javascript based on Google Maps API v3, which sends parameters to the server and receive response data from the server asynchronously. The first operation is to search user’s house or related place in the map. The second step is to select the earthquake from pull-down menu and to confirm the seismic intensity of the place in the hazard map. On this step, surface acceleration waveform is shown and users can adjust start time and duration time. The function to generate pseudo velocity response spectrum, shown in Fig. 4.1 (c), is for experts. In the next step, users select the building type, such as 2F Wooden, 10F RC, etc. Then the system automatically adjusts structural parameters, namely, building shape, dumping factor, and natural period. Experts can input each parameter manually. If all settings are completed, then the Web server calculates one degree of freedom linear response and corresponding earthquake sound at top of the building.

After completion of loading data (structure response, earthquake sound, and browser plugin of the viewer), earthquake response experience simulation and earthquake sound begin. The simulation view is shown in Fig. 4.2 (a), in which the picture moves synchronising with the response displacement. At the bottom of the screen, time series of the ground acceleration and the structure response are shown by green and red lines, respectively. Fig. 4.2 (b) shows the whole building motion in order to check the response amplification between ground surface and top of the building. Fig. 4.2 (c) shows the building model shaking in the real scale with the 3D configuration. Fig. 4.2 (d) shows the floor response from the ceil of the room.

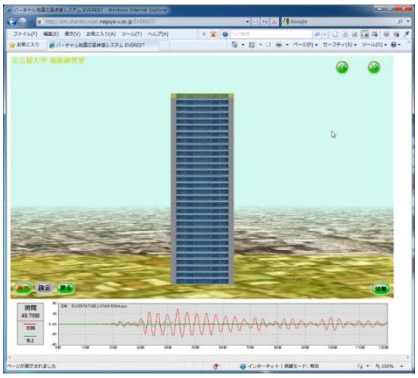
We had released the prototype system on our website, then some users required more reality for the simulation view to impress the building response, since the structure response is shown by moving



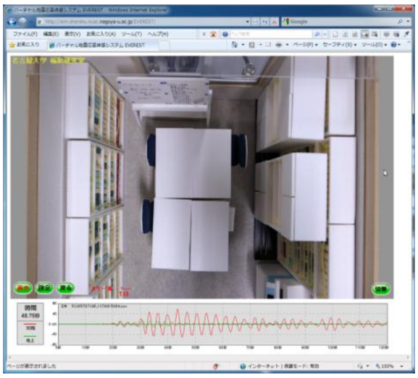
(a) Earthquake experience



(b) Response amplification



(c) 3D model in configuration



(d) Top view of the room

(e) 3D model objects in simulation

Figure 4.2. Screen shots of "EVEREST"

picture in the prototype system. Now we developed the new 3D simulation viewer which shows the motion of building and interior furniture by 3D modelling engine "Unity 3D". This 3D engine has some performance in online 3D game development. Its runtime environment and software development kit are supplied without charge.

The view of 3D simulation is shown in Fig. 4.2 (e). Each object with shade effect and texture effect are shaken by physical logic built in 3D engine. It brings more reality to the simulation, and setting a viewpoint flexibly in 3D modelling virtual space makes users absorbed. Although it is necessary to verify the calculation of shaking motion, the accuracy of 3D simulation is applicable for the purpose of this system.

5. CONCLUSION

We developed the new method to synthesise an earthquake sound from a seismogram using the theory of the symmetrical Fourier analysis. In the method, an earthquake sound is generated combining envelope amplitude of the original seismogram and instantaneous frequency extended to hearable range. Additional tunings on the sound pitch, sound tone, and time series of envelope amplitude are available to synthesise more realistic sound. Some examples of earthquake sound are open on our website. Furthermore, we constructed the Web-based earthquake sound generating system "Naion," in which an arbitrary seismogram can be transformed to corresponding earthquake sound automatically. We also developed the audiovisual earthquake experience system "EVEREST" combining the earthquake sound generating program and the video equipment, which simulates the structure response under assumed ground motion by some earthquakes with synchronised earthquake sound. Other applications would be implemented hereafter.

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