TOWARDS ENHANCING EARTHQUAKE RESPONSE INTERPRETATION USING SONIFICATION

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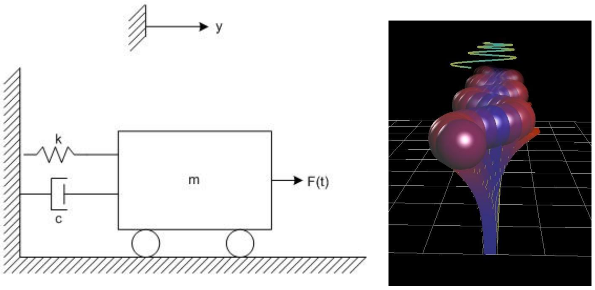
ABSTRACT

In this paper, we select the application domain of earthquake engineering for utility of sonification, where signals are of random frequency and amplitude content. In particular, we focus on the response of structures to particular earthquake time histories. Given a random ground motion input, the resulting response signal will vary in the time and frequency domain, and show large variations in acceleration, velocity and displacement space. We illustrate the utility of different simple, yet robust sonification techniques to the study of the response of a variety of linear elastic single-degree-of-freedom (SDOF) oscillators, with different natural periods T_n and associated damping ratios ζ_n, subjected to a pair of earthquake motions. In the system study, we augment the representation of the response results of these SDOF structures with both visual and aural cues.

1. INTRODUCTION

Sonification is the science of using sound to convey data to the user. The fundamental concept relies upon mapping numerical datasets, of a single or multi-variate nature, into the acoustic domain, with the primary objective of communicating relationships and hence enhancing interpretation within the specific science or engineering field. The field of sonification is fairly young, however, it has more recently become recognized for its potential in supporting visualization tasks.

In this paper, we first present a brief discussion of previous earthquake sonification achievements and subsequently describe our contribution within this domain. We describe our initial application of a sonified visualization framework for the study of the response of simple single-degree-of-freedom (SDOF) oscillator subjected to a pair of earthquake motions. The system of interest is illustrated in Figure 1, where (a) shows an idealization of the mechanical system, and (b) shows our representation of this system, given a few simple visual paradigms to depict the displaced configuration.



(a) (b)

Figure 1: Single-degree-of-freedom system under consideration: (a) mechanical representation with a given stiffness k, mass m, and applied time-varying forcing function $F(t)$ and (b) snapshot of a rendered model illustrating time-varying changes in displacement.

2. BACKGROUND AND RELATED WORK

As early as 1961, sound was used to study earthquake motions. This early work, described in the paper by Speeth [1], presents the idea of using "seismometer sounds", to audify both atomic explosions and natural quakes. The objective was to conduct experiments and ascertain if people could differentiate between the atomic explosion and the earthquake motion, using the generated sounds. Following this study, Frantti and Leverault [2] attempted to verify and quantify the previous results of Speeth, by conducting a survey using listeners trained to distinguish between man-made and natural signals. They report an average success rate of 67.5% for the users capability to identify a natural signal from a blast signal. Until the 1990's, the study of sound for seismological data representation remained relatively dormant, at which time Hayward [3] revived the use of audio to represent seismic waves directly. He conducted an extensive survey on the merits of audification and concentrated on the use of wavelets. Results illustrated that sound spectrum provide a reasonable idea of the variations in the seismic spectrum.

In 1994, an interesting project was presented by Quinn [4], in which the 6.7 magnitude Northridge earthquake in California was translated into a musical composition. The goal was to enable the listener to identify the shape and intensities composed in a seismic wave and on a more psychological level, enable the user to emotionally sense the intensities of an earthquake.

Significant work has been done by Dombois [5], [6] to sonify seismological data. He identified this modality for various purposes, namely, that using sound helps identify the characteristics of techtonic plates and it helps perceive the distance between the site and foci of an earthquake. He acknowledges that diverse tectonic zones respond differently, generating different sounds for them and recognized that information that is hidden in the sound signal during an earthquake can be easily signified using aural cues.

Our work is different than the work described in the above, since we are concerned with sonifying the *systems' response* to earthquake motion input, rather than interpreting and representing the earthquake motion itself. The focus is primarily to use sound to represent the response of idealized buildings, subjected to a broad range of probable earthquake motions.

3. SONIFICATION FOR USE IN INTERPRETING EARTHQUAKE RESPONSE

In this paper, we consider sonification for use in interpreting the response of structures to earthquake motions. In this case, response signals vary in time and frequency domain, and large variations in acceleration, velocity and displacement space may be observed. Thus, such signals are complex and difficult to interpret.

The basis for our sonified-visualization framework is illustrated in Figure 2. It is important to note that the sonification method used in this work is *supplementary*, i.e the visual paradigm is used to hold spatial scale requirements and the aural paradigm is used to add frequency components of the response. Some of these concepts illustrated in the Figure 2 are discussed in the following sections.

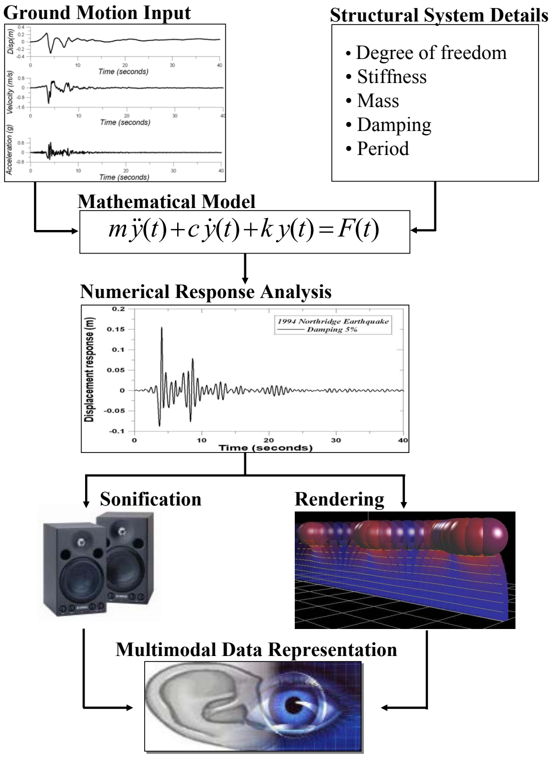


Figure 2: Methodology employed in this study.

3.1. Systems of Interest

The study of sonification can be merged with response of the building structures subjected to earthquake waves. Ground motions travel through a building and cause these structures and articles inside to oscillate in a random, transient fashion. Studying the response of specific structures is necessary to better mitigate damage that may occur. Therefore, in this work our objective is to use sonification to aid in the study of the response of the specific idealization of building structures. Common systems of interest in earthquake building response may be idealized as: (i) Single Degree of Freedom (SDOF) structures responding in the linear, elastic range (simplest), (ii) SDOF structures responding in the nonlinear inelastic range, (iii) Multiple Degree of Freedom (MDOF) structures responding in the linear elastic range, and (iv) MDOF structures responding to nonlinear inelastic range (most complex). To introduce the concepts, in this paper, we focus on the simplest, SDOF, linear, elastic systems for our experiments and results.

3.2. SDOF for Linear Elastic Systems

A free body representation of a single-degree-of-freedom (SDOF) system is illustrated in Figure 1(a). The equation of motion describing the response of this system is given as:

$$m\ddot{y}(t)+c\dot{y}(t)+ky(t)=F(t) \tag{1}$$

where, $F(t)$ is the externally applied force varying with time t, m is the mass of the system, c is the viscous damping coefficient, and k is the elastic stiffness of the system. The response of the system may be determined by either numerically or analytically solving Equation 1. The resulting response may be represented in either displacement $y(t)$, velocity $\dot{y}(t)$, or acceleration $\ddot{y}(t)$ space. Clearly, the response of the system depends on the nature of the forcing function $F(t)$.

A system can be subjected to harmonic loading if the forcing function $F(t)$ is sinusoidal in nature. The equation of motion of the body may then be described as:

$$m\ddot{y}(t)+c\dot{y}(t)+ky(t)=F_o sin(\omega_n t) \tag{2}$$

where F_o is the initial amplitude of the force and ω_n is the forcing functions frequency. The solution to the above equation consists of two parts: (i) a transient term and (ii) a steady state term. The transient term gets attenuated to zero and hence need not be considered. The steady state term depends on the damping ratio ζ ($\frac{c}{c_r}$, where c_r = critical damping coefficient) and the frequency ratio ($r=\overline{\omega}/\omega_n$). However, the external force is not always zero or sinusoidal. There are many conditions when the load is a complex combination of different signals. Response to general loading can be obtained by using Duhamel's Integral or by using Fourier Transforms [7]. The concept of Duhamel's Integral allows consideration of complex loading by applying piecewise integration of impulsive functions. The superposition of all these loads can be considered as the original load. The total displacement may be determined by integrating a small displacement over time τ.

Due to the complex nature of seismic motions, it is difficult to use Duhamel's Integral directly to solve for the response analytically. The easiest way to solve such complicated inputs is to use a numerical evaluation.

3.3. Fundamental Mapping Concepts used in this Study

Within the field of earthquake engineering, most commonly, the response is studied using graphs or plots, in the time or frequency domain. However, if multiple systems or response parameters are to be considered, new modalities need to be identified to separate response characteristics of interest. We therefore describe several simple, yet robust approaches to map the characteristics of the earthquake response signal to sound.

Due to the aforementioned complex nature of the seismic waves, and the natural spatial segregation of the signal into both time and frequency space, we broadly categorize the approaches as either (i) frequency-based or (ii) time-based. Our acoustics engine, relies on the sequential application of the concepts illustrated in Figure 3.

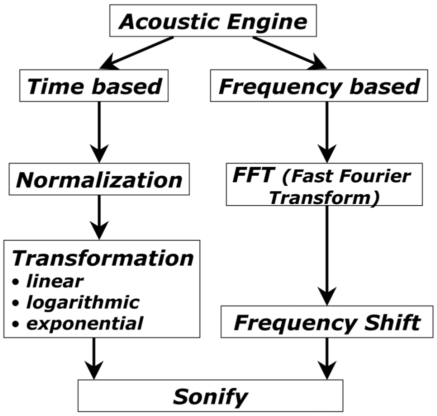


Figure 3: Methodology employed within the acoustics engine for mapping earthquake response signals.

Frequency-Based: Given a waveform, its frequency provides an inherent, natural property of the signal. To be able to *listen* to the frequency of that wave, it is essential to shift the frequency content of that waveform to the audible range (between 20 – 20,000 Hz). Given a time-domain signal, one first must convert the signal into the frequency-domain. Transformations may then be applied using various mathematical forms (linear, logarithmical, exponential, parabolic, quadratic, etc.).

Time-Based: Amplitudes of the given wave form may also be shifted to the audible range by a simple linear transformation within the time-domain. This type of transformation is a form of *Amplitude Modulation*. However, seismic waves have both positive and negative amplitudes. Clearly, negative values cannot be idealized using sound and thus the data must be represented in the positive regime, while still preserving the oscillatory nature (minima and maxima nature) of the signal. We therefore normalize our time-domain signal by the absolute value of the maximum amplitude of the signal. An example of this approach is shown in Figure 4.

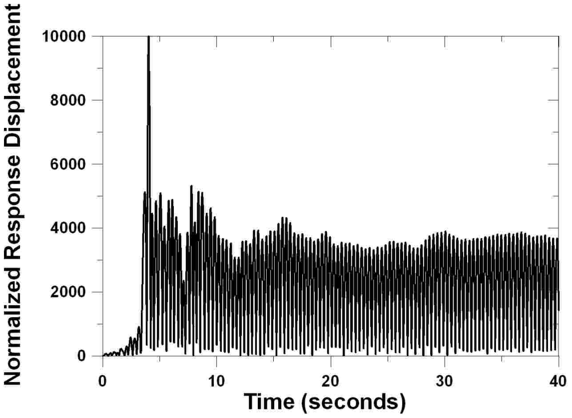


Figure 4: Signal pre-processing in time domain that illustrated amplitude modulation and normalization.

4. SONIFICATION EXPERIMENTS AND RESULTS

The study of sonification can be merged with the response of building structures subjected to earthquake waves. Ground motions travel through a building and cause these structures and articles inside to oscillate in a random, transient fashion. Studying the response of specific structures is necessary to better mitigate damage that may occur.

4.1. Process of Sonification Experiments

Most of the techniques discussed here are very simple in nature, since our focus is to provide a proof-of-concept framework. In this study, we selected two earthquake time histories as input motions to our analytical representation, one measured from the 1994 Northridge earthquake, and the other a synthetic earthquake motion created for the design of the new San Francisco Bay Bridge in California, U.S.A. Given the previous discussion, our method follows the process described below.

(1) Numerical evaluation of the equation of motion (Equation 1) is first conducted, using the central difference method, to obtain response displacement. Results were obtained for systems with two different natural periods, $T_n = 0.3 sec$, $T_n = 0.7 sec$ and for a single mass $m = 10 lb$. A natural period of T_n = 0.3sec is fairly representative of a stiff SDOF system, whereas a natural period of T_n = 0.7sec represents a fairly flexible structure. The stiffness coefficient k varies proportional to mass m and is inversely proportional to T and may be back-calculated as $k = 4\pi^2 \frac{m}{T_n^2}$. It may be noted that, in this case, we consider the response component of relative displacement, however one could just as easily differentiate and consider velocity or acceleration.

(2) Since realization of negative values in the aural domain is not possible, values are normalized. The positive response displacement values are mapped to the audible range by performing a linear transformation, as illustrated in Figure 4.

(3) Sonification is then implemented in both time and frequency space. In the time-domain, the amplitude of the response displacement are mapped to the loudness of the sound. To map in the frequency domain, a fast fourier transform is performed on the displacement time signals. These frequency values, however, are not necessarily in the audible range, therefore they are normalized and linearly shifted by a selected frequency increment, Δf.

(4) The final step is the generation of the sound wave using *CSound*. [8]. *CSound* requires an orchestra file where the actual data is provided and a score file where the waveform specifications such as sample rate, audio rate and the channels used are input.

4.2. Numeric Plots

Since there exists a technical incapability to represent sound in a paper, select waveforms for each of the response calculations are provided instead. Figure 5 shows a sample of response calculations for T_n = 0.7 seconds and corresponding damping of ζ_n = 0% and 5% from the Synthetic motion. From this figure, one can see the dramatic difference observed in the response when damping is considered (or not) in the response. Comparing the analysis results of T_n = 0.3 sec and 0.7 sec, the response displacement is observed to maintain a higher frequency for the lower period system selected, and vice versa.

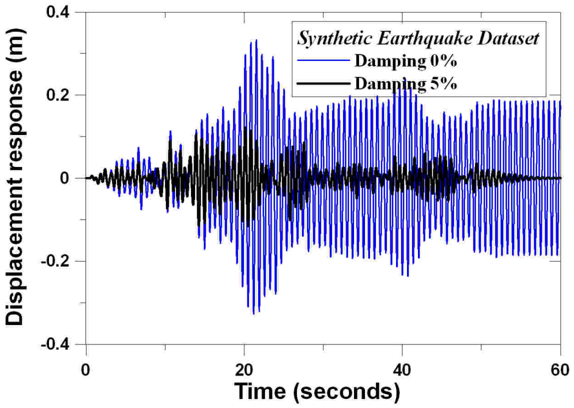


Figure 5: Sample response displacement plots for T_n = 0.7 seconds and ζ_n = 0% and 5%, subjected to the Synthetic earthquake motion.

4.3. Visual Representation of System Response

An important aspect of sonification is that sound should be accompanied with visual cues to provide enhanced understanding. Since the response displacements were generated for an SDOF system, a simple yet robust generic model of the SDOF system was generated using a *Ball and Stick* model to idealize the mass and the column, respectively.

A simple cuboid was used as a geometric primitive for representing the column. The column was itself constructed using ten such cuboids with each cuboid capable of movement when subjected to the ground motion giving rise to a flexible column as seen in the Figures 1. The displacement of each slice (cuboid) of the column may be determined considering successive integration of Euler Bernoulli beam theory.

A key feature of the visualization is the use of colors and transparency to convey information. We use transparency to signify the temporal domain and color to code displacement response values. Time is mapped to the z-axis and as time advances, the transparency is reduced producing a ghosting effect. Color coding is used to map displacement changes with blue signifying the lowest displacement and red signifying the maximum displacement. The sinusoidal above the structure represents the trace of the movement of the structure in time [Figure 1]. This visual rendering, combined with aural cues, provides a multimodal representation of the displacement response changing in time.

5. CONCLUSIONS

Sonification provides a powerful tool for more fully utilizing the available human senses for data analysis and interpretation. Previous studies have combined sonification techniques with visualization to enhance communication and overall understanding of scientific and engineering datasets. Such studies have proven the strength of this added modality. However, few studies have considered science and engineering datasets with respect to response parameters, which have implications in both time and frequency space. The presented mapping technique, using time and frequency space, match the nature of sound, thereby contributing greatly towards representation of such datasets. In this paper, we select the application domain of earthquake engineering for utility of sonification, where signals are of random frequency and amplitude content. In particular, focus is on the response of structures to a given earthquake time history. In this case, response signals vary in both time and frequency domain, while large variations in acceleration, velocity and displacement space may be observed.

Future Work – A detailed study needs to be conducted to evaluate the users' capabilities to better interpret seismic response, using the method proposed. For this, we will select a group of civil engineers as the study set and replay for them simulations, incorporating our sound cues synchronized with visual representations. Critical to setting up our user study space is the design of a suitable sound and visual setting for participants. For our work, we are implementing a 4.1 sound system within a fully digital combined educational-research space, *VizClass* [9]. The final sound system selected for this space was the *Alesis* monitor system. With a frequency response of 38 Hz - 23.5 kHz, this system is controlled via an *M-Audio* Delta 1010LT PCI controller with 8 input and 8 output analog channels.

ACKNOWLEDGEMENTS

This research is supported by the National Science Foundation, under Grant Number EIA-0203528. In addition, we acknowledge the helpful comments of Dr. Thomas Hermann during this work. The above support is greatly appreciated.

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