GENERATION OF MULTIPLE SPECTRUM-COMPATIBLE ARTIFICIAL EARTHQUAKE ACCELEGRAMS WITH HARTLEY TRANSFORM AND RBF NEURAL NETWORK

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ABSTRACT

The Hartley transform, a real-valued alternative to the complex Fourier transform, is presented as an efficient tool for the analysis and simulation of earthquake accelerograms. This paper is introduced a novel method based on discrete Hartley transform (DHT) and radial basis function (RBF) neural network for generation of artificial earthquake accelerograms from specific target spectrums. Acceleration time histories of horizontal earthquake ground motion are obtained by the capability of learning of RBF neural network to expand the knowledge of the inverse mapping from the response spectrum to earthquake accelerogram. In the first step, Hartley transform is used to decompose earthquake accelerograms, then a RBF neural network is trained to learn to relate the response spectrum to Hartley spectrum. Finally, the generated accelerogram using inverse discrete Hartley transform is obtained from target spectrum. Approximately 200 uniformly scaled horizontal ground motion records from recent Iran’s earthquakes are used to decompose with real Hartley transform and train networks.

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KEY WORDS: Hartley transform, RBF neural network, artificial earthquake accelerograms

1. INTRODUCTION

In recent years, dynamic analysis of structures, either time-history of earthquake ground motion or response spectrum has grown considerably. Time histories also are used to
correlate ground motion characteristics to structural and non-structural damage. In addition, for designing critical or major structures such as power plants, dams, and high-rise buildings, usually the final design is based on the complete time-history analysis.

In most cases, it is very unlikely that recorded ground motions will be available for all sites and conditions of interest. Hence, accurate methods for the simulation of earthquake ground motion throughout a region that utilize ground motions from previous earthquakes and recorded motions from the earthquake that has just occurred and according to a design spectrum is needed. Simulated accelerograms should have two important characterizes: first, be according to a specific design spectrum and second, have compatible geotechnical characteristics with desired area. There are so many methods for generating spectrum-compatible artificial earthquake accelerograms. Many researchers generate artificial accelerograms by modifying available accelerograms. These methods include applying a constant scalar to well-populated data banks [1, 2] or modifying them in time or frequency-domain. In the time-domain approaches usually recorded time histories passed through filters (e.g. Kanai-Tajimi filter) to alter the amplitude or frequency content over time. By using simple Fourier analysis and calculating the Fourier amplitude and phase angle spectra of historical accelerograms and then modifying the phase angle spectra, spectrum-compatible accelerograms with similar frequency content but different temporal characteristics can be obtained [3].

These methods applied to the analysis and simulation of earthquake records are based on the use of the discrete Fourier transform, whose success is largely due to the existence of efficient algorithms that known as fast Fourier transform (FFT) algorithms, for their computation. Nevertheless, the practical use of Fourier methods shows some drawbacks in the analysis of time series that observed in nature. Especially, while signals observed in most real-word applications are real-valued the Fourier transform, transforms a sequence of real data from the time-domain into a sequence of complex numbers in the frequency-domain. So, half of the numbers in the frequency-domain correspond with the information in the negative frequencies and are the same as the information contained in the positive frequencies. Additionally, this means that FFT algorithm required twice memory space of a real array. Furthermore, the multiplication of two complex numbers requires four real multiplications and two real additions. Consequently, due to the extra information, the amount of memory required and the number of computations needed, it seems obvious that the complex Fourier transform is not the most efficient method to transform real time series into the frequency domain.

Hartley proposed a real transform to avoid the time and memory computation shortcomings related to the complex Fourier transform of real data. This transform was expressed in a more symmetrical form between the function of the real variable and its transform. Nevertheless, because of introduction of discrete Cosine transform a little after Hartley transform and the similarity of them, Hartley transform remain unknown between researchers [4,7].

The main purpose of the present paper is to introduce the Hartley transform as an efficient tool and convenient alternative to the traditional complex Fourier transform for analysis and simulation of earthquake records and comparing the results with wavelet transform.
2. THE HARTLEY TRANSFORM

The integral Fourier transform of a continuous function of time \( x(t) \) is given by [5]:

\[
F_x(f) = \int_{-\infty}^{\infty} x(t)e^{-i2\pi ft} \, dt
\]  

(1)

The inverse transform is defined as:

\[
x(t) = \int_{-\infty}^{\infty} F_x(f)e^{i2\pi ft} \, df
\]  

(2)

and the kernel transform function is:

\[e^{i2\pi ft} = \cos(2\pi ft) \pm i \sin(2\pi ft)\]  

(3)

In engineering problems, for using Eqs. (1) and (2) we should discrete data over a finite range. Therefore, a discrete approximation of above equation is needed. The discrete Fourier transform (DFT) is defined as [6]:

\[
F_x(k) = F(k\Delta f) = \sum_{n=0}^{N-1} x(n)e^{-i2\pi nk/N} \quad k = 0,1,\ldots,N-1
\]  

(4)

Where \( N \) is the number of samples, \( \Delta t \), the constant sampling period, and \( T = N\Delta t \), the total duration of the digitized time series, and also for a fixed \( N \), the time and frequency increments are constrained by \( \Delta f/\Delta t = 1/N \). The original time series can be calculated by IDFT that written as:

\[
x(n) = \frac{1}{N} \sum_{k=0}^{N-1} F_x(k)e^{i2\pi kn/N} \quad n = 0,1,\ldots,N-1
\]  

(5)

In the engineering applications, there are signals that are limited, but have unlimited energy, for example periodic functions. So, we cannot use Eq. (1) for their Fourier transform. For this functions, we can either assume a period of signal and solve the problem or use the Stieltjes integration instead of Lebesque integration. We assume here that \( x(t) \) has limited energy.

The Hartley transform of a real-valued function \( x(t) \) defined as [6]:

\[
H(f) = \int_{-\infty}^{\infty} x(t)\cos(2\pi ft) \, dt
\]  

(6)

and the inverse Hartley transform given by:
\[ x(t) = \int_{-\infty}^{+\infty} H(f) \text{cas}(2\pi ft) df \]  

(7)

where the kernel function of Hartley transform is defined as:

\[ \text{cas}(x) = \cos(x) + \sin(x) \]  

(8)

It is interesting to note that the Hartley transform has a self-inverse property that means the direct and inverse of transformations use the same integral operation [7].

Just like the Fourier transform, the practical use of the Hartley transform equations (Eqs. 6 and 7) of the sampled real-valued finite time series \( x(n) \) requires the use of discrete approximations. The discrete Hartley transform (DHT) is given by [6]:

\[ H(k) = H(k \Delta f) = \sum_{n=0}^{N-1} x(n) \text{cas}(2\pi k \Delta fn \Delta t) \quad k = 0,1,...,N - 1 \]  

(9)

The inverse discrete Hartley transform (IDHT) can be written as:

\[ x(n) = \frac{1}{N} \sum_{k=0}^{N-1} H(k \Delta f) \text{cas}(2\pi kn / N) \quad n = 0,1,...,N - 1 \]  

(10)

Note that Eqs. (9) and (10) have exactly the same form, except for a scaling factor of \( 1/N \). This implies that the forward and inverse transforms satisfy the self-inverse property. As a consequence, both the DHT and the IDHT can be computed by using the same algorithm. Furthermore, while the Fourier transform of a real signal is a complex function, the Hartley transform of a real function is also real because of the real nature of the cas function [7].

3. THE RBF NEURAL NETWORK

A radial basis function (RBF) network is an artificial neural network that uses radial basis functions as activation functions. It is a linear combination of radial basis functions. RBF networks typically have three layers: an input layer, a hidden layer with a non-linear RBF activation function and a linear output layer. The architecture of a radial basis function network can be shown as Fig.1. In comparison with back propagation networks, RBFs have several advantages. They usually train much faster than back propagation networks. Also, they are less susceptible to problems with non-stationary inputs because of the behavior of the radial basis function hidden units.

In a RBF network, there are three types of parameters that need to be chosen to adapt the network for a particular task: the center vectors, the output weights, and the RBF width parameters. In the sequential training of the weights are updated at each time step as data streams in. For some tasks, it makes sense to define an objective function and select the parameter values that minimize its value.
The studies of Fourier, energy, power, and response spectra show that though the patterns of different earthquake records are not similar even in a specified area, but a certain pattern of response spectra could often be attained for the specified area because of their similarities [8].

The main objective of this paper is to analysis earthquake records with Hartley transform and training neural networks that are capable of generating multiple accelerograms for specified input response spectrum that includes the site geology specifications of a specified site. The generated accelerograms should have response spectrums closely approximate to the input response spectrum. In addition, the other characteristics of the generated accelerograms, such as their duration, should be similar to those of the recorded accelerograms used to train the neural networks.

4.1 Input earthquake accelerograms

One of the most important factors that influenced earthquake ground motions is local soil conditions. Recent studies of the influence of site geology on ground motion use the average shear wave velocity to identify the soil category. Also, there is a general agreement among various investigators whom the soil condition has a pronounced influence on velocities and displacements, thus larger peak horizontal velocities are to be expected for soil than rock [9,10]. This important factor is not taken in the models of previous related works. So, we categorizing earthquake records into two groups named Soil and Rock according to Iranian seismic design code [11]. According to this category soil with $375 \leq V_s$, named Rock and others with $375 > V_s$, are Soil.

Then, we categorize all record into four duration groups of 10, 20, 30 and 40 seconds. For better result and faster training of NN, peak ground acceleration (PGA) of all accelerograms in each group shifted to make the PGA of each accelerogram aligned at the same time. This operation is performing by adding or deleting zeros from the start or end of accelerograms in specified manner so navigates of them not changed. Next, PGA of all the accelerograms were scaled to 1g so we could compare their response spectrum. In Tables 2 to 8 all records and categorizes that used for training RBF networks are shown. Note that researchers for Soil group with 10 seconds duration could not find any suitable records.
Table 1: Site Geology according to Iranian seismic design code [11].

<table>
<thead>
<tr>
<th>Ground type</th>
<th>Explanation of materials</th>
<th>Shear wave velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Un-weathered igneous rocks, hard sedimentary rocks and metamorphic rocks (as gneisses and crystalline silicate rocks)</td>
<td>$V_s &gt; 750$</td>
</tr>
<tr>
<td></td>
<td>Very hard conglomerates very compact and very hard sediment</td>
<td>$375 &lt; V_s &lt; 750$</td>
</tr>
<tr>
<td>II</td>
<td>Crushed (but not hardly) hard rocks, foliated metamorphic rocks, conglomerate and compact sand and gravel</td>
<td>$375 &lt; V_s &lt; 750$</td>
</tr>
<tr>
<td>III</td>
<td>Weathered rocks, semi-compact sands and gravels, other compact sediments</td>
<td>$175 &lt; V_s &lt; 375$</td>
</tr>
<tr>
<td></td>
<td>Soft sediments, clay soils, weak cemented and un-cemented sands, uncompacted soils</td>
<td>$V_s &lt; 175$</td>
</tr>
</tbody>
</table>

Table 2. List of earthquake records used as training set of ANN, group of 10 sec duration, Site geology: Rock [12].

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Station</th>
<th>Date</th>
<th>Magnitude</th>
<th>Modified PGA (cm/sec²)</th>
<th>Duration (sec)</th>
</tr>
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<td>761</td>
<td>9</td>
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<tr>
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<td>8.34</td>
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<td>32.8</td>
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<tr>
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<td>27.6</td>
<td>8.3</td>
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<td>84</td>
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<td>397.3</td>
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Table 3. List of earthquake records used as training set of ANN, group of 20 sec duration, Site geology: Rock [12].

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<tr>
<th>Earthquake</th>
<th>Station</th>
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<th>Magnitude</th>
<th>Modified PGA (cm/sec²)</th>
<th>Duration (sec)</th>
</tr>
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Table 4. List of earthquake records used as training set of ANN, group of 30 sec duration, Site geology: Rock [12].

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<th>Earthquake</th>
<th>Station</th>
<th>Date</th>
<th>Magnitude</th>
<th>Modified PGA (cm/sec²)</th>
<th>PGA</th>
<th>Duration (sec)</th>
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Table 5. List of earthquake records used as training set of ANN, group of 40 sec duration, Site geology: Rock [12].

<table>
<thead>
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<th>Earthquake</th>
<th>Station</th>
<th>Date</th>
<th>Magnitude $M_S$</th>
<th>Modified PGA (cm/sec$^2$)</th>
<th>Duration$^+$ (sec)</th>
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5. RESPONSE SPECTRUM

In the previous works, some researchers use pseudo-velocity response spectrum (PSV) as inputs [13] and others use pseudo-acceleration response acceleration (PSA) [14]. For present research, both PSV and PSA are used for training networks separately to compare the results and recognizing that which of them is more suitable for our purpose. The values of the response spectrums of accelerograms are calculated at 1001 discrete frequencies according to the following formula [15].

\[
\ddot{x}(t) + 2\zeta\omega_0\dot{x}(t) + \omega_0^2 x(t) = -a_g(t), \quad (11)
\]

\[
PSV(\omega_l, \zeta) = \omega_l \max_{t} |x(t)|, l = 1, 2, 3, \ldots, 1000, \quad \zeta = 5\%, \quad (12)
\]

\[
PSA(\omega_l, \zeta) = \omega_l PSA(\omega_l, \zeta) = \omega_l^2 \max_{t} |x(t)|, l = 1, 2, 3, \ldots, 1000, \quad \zeta = 5\%, \quad (13)
\]

where \(\omega_0\), \(\zeta\) and \(a_g(t)\) are the fundamental frequency and the damping coefficient of the single degree of freedom system and the earthquake ground acceleration, respectively.

6. TRAINING AND TESTING OF RBF NEURAL NETWORKS

As mentioned before the main subject of this paper is using ANNs to mapping a relation between response spectrum of training accelerograms and Hartley spectrum of them. Note
that because of real nature of Hartley transform we do not have any imaginary numbers. So, ANNs easily trained.

For training, in each category we pick all records except two of them, randomly. Then, PSA and PSV and also Hartley spectrum of them will be calculated. Next, one time we train networks with PSV of records as input and Hartley spectrum of them as target. The other time we replace PSV with PSA and repeat the process.

After training we control the networks by testing them in two steps. First, calculate PSV and PSA of records that was in training groups. Then, we obtain Hartley spectrum of records from trained RBF neural network. After that, with taking inverse discrete Hartley transform (IDHT) of Hartley spectrum, simulated records are obtained. For this step original and simulated records and response spectra should be the same. Second, calculate PSV and PSA of two records that was not in training group. Finally, PSA and PSV of them are calculated so that we can control with PSA and PSV of original records.

7. INTERPRETIVE EXAMPLES

187 earthquake accelerograms recorded in Iran is used for training the ANNs, that all of these records were discretized at 0.005 seconds. Therefore, all accelerograms with durations of 10, 20, 30, and 40 sec. have 2001, 4001, 6001, and 8001 discrete points, respectively. 

PSA or PSV spectra of all accelerograms are calculated numerically, according to Equations 11 to 13 at 1001 equally spaced discrete period in the range of 0.01-10s, with 5% damping ratio (ζ=5%). Comparison between original and simulated records that were in trained groups are shown in Fig.2 and 3.

As can be seen, the ANNs learn the relation between response and Hartley spectra very
well and simulated and original records are exactly the same. In Fig.4 and 5 comparisons between records that were not in training group are shown.

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**Figure 3.** Controlling RBF network with train records, Nasrabad-1999, Soil, 30 sec.

**Figure 4.** Controlling RBF network with train records, Sepidan-2000, Rock, 20 sec.

As can be seen, response spectra of simulated records for PSA and PSV are very similar to original records. So, it’s clear that RBF neural networks learns the relation between response and Hartley spectrum of records and can simulate them very well.
Finally, figures 6 to 9 show the generated varied duration accelerograms from Newmark and Hall (Newmark & Hall, 1986) with PGA 1g and mean hazard level for Rock and Soil geology.

As shown in this figures, result from PSA and PSV are different. Also, artificial accelerograms from PSA are very noisy. Another matter is that the response spectrums of...
artificial accelerograms for period of 1 second and upper are similar to design spectrum approximately well.

Figure 7. Generated 30 sec. accelerograms from Newmark and Hall design spectrum, Rock.

Figure 8. Generated 20 sec. accelerograms from Newmark and Hall design spectrum, Soil.
8. CONCLUSIONS

In this study, first a method of applying Hartley transform in analysing earthquake accelerograms introduced and then by using the capability of RBF neural networks in learning nonlinear problem, multiple spectrum-compatible artificial accelerograms for two site type of Rock and Soil are generated. 187 earthquake accelerograms recorded in Iran are used for training the ANNs, that all of these records were discretized at 0.005 sec. Then all these categorized according to their durations of 10, 20, 30 and 40 seconds. PSA or PSV spectra of all accelerograms are calculated numerically, according to Equations 11 to 13 at 1001 equally spaced discrete period in the range of 0.01-10s, with 5% damping ratio (ζ=5%).

The inputs of ANNs are PSA and PSV and targets of them are Hartley spectrum. After training and testing neural networks in each category (Figs 2 to 5), for given design spectra RBFs generate artificial acceleration with duration of their category (Figs 6 to 9). The artificial accelerograms have accidental nature of real earthquake. But their response spectra match to the design spectra only for periods more than 1 sec. very well.

REFERENCES

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