Research on Influencing Factors and Generalized Power of Synthetic Artificial Seismic Wave

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Abstract. Start your abstract here… In this paper, according to the trigonometric series method, the author adopts different envelope functions and the acceleration design spectrum in Seismic Code For Urban Bridge Design to simulate the seismic acceleration time history which meets the engineering accuracy requirements by modifying and iterating the initial wave. Spectral analysis is carried out to find out the distribution law of the changing frequencies of the energy of seismic time history and to determine the main factors that affect the acceleration amplitude spectrum and energy spectrum density. The generalized power formula of seismic time history is derived from the discrete energy integral formula and the author studied the changing characteristics of generalized power of the seismic time history under different envelop functions. Examples are analyzed to illustrate that generalized power can measure the seismic performance of bridges.

1. Introduction
In the evaluation of seismic performance, time history analysis is mature and practical[1]. With the development of IT and finite element, it’s getting common to take time history analysis during the earthquake into consideration in structures’ aseismic design. Thus one problem of transient response analysis of structures is how to choose an appropriate seismic wave needed in time history analysis to make the calculation result reflect the structure’s actual vibration. The output of time history analysis of existing seismic records conforms the most to the actual situation. But most of the fields don’t have their own records. Due to the distinction among different fields, there’s huge margin of error in the calculation result of other filed’s seismic records to the actual response result and therefore the result is invalid. And the records of seismic wave is not adequate enough to meet the need’s of engineering anti-earthquake. As a result, using design response spectrum to simulate seismic wave gets researchers’ attention and gets developed. Levy and Wilkinson study on the effects of acceleration time 0 and 180 degree of phase angles and frequencies on the accuracy of acceleration response spectrum[2], Jun et al. put forward a method of synthesizing artificial seismic waves by using the general conditions of building fields. The random vibration method is established through using the spectral density function by Vanmarcke to synthesize seismic waves[3]. Tsaiand explores on the method for obtaining a smoothly computed response spectrum[4]. Kost et al uses Fourier Series Theory, defining the initial acceleration time history, using the proportionality coefficient between the design acceleration response spectrum and the calculation acceleration response spectrum to simulate the acceleration time history curve[5]. Aziz and Biswas make a summary of all the methods of synthesizing acceleration and use these methods for the seismic analysis of nuclear reactor buildings[6]. Gangsig Shin uses time domain method to establish the artificial seismic waves in line with the site condition[7]. Kang Peng
uses Wavelet Transform and non smooth acceleration response spectrum to fit the artificial seismic wave\cite{[8]}. Zhao and Zhang propose a fitting method which meet the specified PGA, PGV, PGD and the target response spectrum\cite{[9]}. All the methods above don’t have an analysis on the synthesis of artificial acceleration amplitude spectrum and power spectrum density. Therefore this paper adopts the trigonometric series method to simulate a number of artificial seismic waves which meet the requirement of engineering precision for bridges’s aseismic function. The author makes further study on the influences of different envelop functions on artificial acceleration time history amplitude spectrum and power spectrum density under the same target spectrum, derives the generalized power formula of seismic time history from the discrete energy integral formula and studies the changing characteristics of generalized power in seismic time history under different envelop functions.

2. Synthesis of Artificial Waves

2.1. The Basic Theories of Synthesizing Artificial Waves

The common method of synthesizing artificial ground motion is to regard the ground acceleration time history as a non-stationary random process. The acceleration of the ground motion is usually expressed by the product of a time-varying intensity function and a stationary process as follows:

\[ x(t) = f(t) \cdot p(t) \]  \hspace{1cm} (1)

where \( f(t) \) is a intensity envelope function and \( p(t) \) is a stationary process.

The measured seismic acceleration is a complex periodic function, and the Fourier Series can be used to synthesize any periodic function. Therefore the Fourier Series can be used to synthesize the stationary process of seismic acceleration as follows:

\[ p(t) = \sum_{k=1}^{N} c_k \cos(\omega_k t + \phi_k) \]  \hspace{1cm} (2)

Where \( c_k \) and \( \omega_k \) are the amplitude value and frequency value of the \( k \) in the Four Series, and \( \varphi_k \) is the uniform random number of \((0,2\pi)\).

\( c_k \) and \( \omega_k \) are defined by\cite{[10]}:

\[
\begin{aligned}
    c_k &= \left[4S(\omega_k)\Delta\omega\right]^{1/2} \\
    \Delta\omega &= 2\pi / T_d \\
    \omega_k &= \Delta\omega k \quad (k = 1, 2, \cdots, N)
\end{aligned}
\]  \hspace{1cm} (3)

2.2. Relationship between Response Spectrum and Power Spectrum

2.2.1. Relationship between Stationary Process Response Spectrum and Power Spectrum

Kaul\cite{[11]} puts forward the approximation relation between stationary process response spectrum and power spectrum as follows:

\[
S(\omega_k) = \frac{\xi}{\pi \omega_k} \left[ S_a(\omega_k) \right]^{1/2} \frac{1}{-\ln \left[ \frac{-\pi}{\omega_k T} \ln(1-p) \right]}
\]  \hspace{1cm} (4)

Where \( S_a(\omega_k) \) is an objective function, \( \xi \) is the damping ratio, \( P(\equiv 15\%) \) \( p \) is the probability of the average amplitude of calculated response spectrum exceeding that of the target response spectrum, and \( T \) is the total duration of seismic acceleration.

2.2.2. Relationship between Non-Stationary Process Response Spectrum and Power Spectrum
Considering the non-stationarity of the ground motion, Jiang Jinren, a scholar of China, puts forward the distribution of maximum responses under non-stationary input and based on the distribution the relationship between power spectrum and average amplitude response spectrum is established[12].

$$M = \frac{t_t - 0.3t_t}{\tau} + \frac{1}{2\xi\omega\tau} \left( e^{-2\xi\omega_1\tau} - e^{-2\xi\omega_2\tau} \right) + \frac{1}{ct} \left[ 1 - e^{\left( \frac{t_t + 0.5 - t_t}{2} \right)} \right]$$

(5)

$$S(\omega_k) = \frac{4\xi[S_T(\omega_k)]^2}{\pi \omega_k M \left[ (2\ln\nu\tau)^{1/2} + \frac{0.5772}{(2\ln\nu\tau)^{1/2}} \right]^3}$$

(6)

where $S(\omega_k)$ is power spectrum; $\tau$ is the finite duration of equivalent stationary perturbation in place of non-stationary perturbation, $\tau = t_t + \frac{2\ln 2}{c} - \frac{t_t}{2}$; $\nu \approx \frac{\omega}{\pi}$; $S_T(\omega_k)$ is the target spectrum.

2.3. Two Forms of Intensity Envelop Function

There are three stages in seismic acceleration: rising acceleration, stable acceleration and drooping acceleration. The stationary waveform is multiplied by an appropriate deterministic time function, and is transformed into a non-stationary form which is suitable for the designed or the largest magnitude of the possible earthquake and the distance from the source to the site. Deterministic time function is intensity envelop function. At present, there are two form of intensity envelop function.

![Unimodal envelop function](image1)

![Piecewise envelop function](image2)

2.3.1. Unimodal Continuous Intensity Envelop Function

Unimodal continuous function [13] as shown in Fig.1

$$f(t) = W_0 \left[ \exp(-at) - \exp(-bt) \right]$$

(7)

The peak position and intensity envelopes of the ground motion is determined by parameter $a$ and $b$.

Jyengar[14] puts forward the model as follows:

$$f(t) = (a + bt)\exp(-ct)$$

(8)

$a$ is an initial intensity value, $c$ controls the changing speed of the peak point, and $a$ , $b$ and $c$ decide the position of the peak point and the shape of the envelop together.

Clough[15] puts forward the model as follows:

$$f(t) = a_t \exp(-a_z t)$$

(9)

For the general type of acceleration time histories recorded in the San Fernando earthquake in California, statistical studies show that the constants $a_t$ and $a_z$ are assigned to 0.45 and 1/6 respectively.

2.3.2. Piecewise Intensity Envelop Function

Jennings\textsuperscript{[16]} proposes the intensity envelop function in piecewise form as shown in Fig. 2

\[
f(t) = \begin{cases} 
\left( \frac{t}{t_1} \right)^2 & t < t_1 \\
1 & t_1 \leq t \leq t_2 \\
\exp\left[ -c(t-t_3) \right] & t_2 < t \leq t_4
\end{cases}
\] (10)

where \( c \) controls the speed of the decay portion, \( t_1 \) and \( t_2 \) control the beginning and ending point of the stationary portion respectively, \( t_3 \) is the seismic acceleration duration and \( T_d = t_3 \) in general.

2.3.3. Determination of the parameters of unimodal intensity envelop function

To decide the parameters of intensity envelop function, the parameters in Table 1 can be selected if there is no data of magnitude and epicentral distance\textsuperscript{[17]}.

Table 1. Selection of parameters in different durations.

| Duration(s) | Relevant parameters | Damping coefficient \( c \) |
|-------------|---------------------|--------------------------|
| 5           | 0.5                 | 4                        | 5                        | 1.50                     |
| 10          | 1.0                 | 7                        | 10                       | 1.15                     |
| 20          | 2.0                 | 16                       | 20                       | 0.80                     |
| 30          | 3.0                 | 25                       | 30                       | 0.64                     |

If there is data of magnitude and epicentral distance, \( t_1, t_2 \) and \( c \) can be calculated by the regression formula\textsuperscript{[18]} as follows:

\[
\begin{align*}
\lg t_1 &= -1.074 + 1.005 \lg (D + 10) \\
\lg t_2 &= -2.268 + 0.3262M + 0.5815 \lg (D + 10) \\
\lg c &= 1.941 - 0.2871M - 0.567 \lg (D + 10)
\end{align*}
\] (11)

where \( M \) is equivalent earthquake magnitude, \( D \) is equivalent epicentral distance, \( t_s \) is the duration of seismic stationary portion, and \( t_2 = t_1 + t_s \)

2.4. Determination of Objective Function

According to the designed acceleration response spectrum in Seismic Code For Urban Bridge Design, the required parameters can be decided, as shown in Fig. 3

![Figure 3. Designed acceleration response spectrum](image-url)
where $S_{\text{max}}$ is 2.25 times the peak acceleration of ground motion, $T_g$ is the period of site characteristic, $\eta_1$ and $\eta_2$ are damping. There are specific descriptions in the norms for adjustment coefficient.

$$S^T(T) = \begin{cases} \left[ T(\eta_1 - 0.45) \times 0.1 + 0.45 \right] S_{\text{max}} & 0 \leq T \leq 0.1 \\ \eta_2 S_{\text{max}} & 0.1 < T \leq T_g \\ \eta_2 S_{\text{max}} \left( \frac{T}{T_g} \right)^\gamma & T_g < T \leq 5T_g \\ \left[ \eta_1 0.2^\gamma - \eta_2 (T - 5T_g) \right] S_{\text{max}} & 5T_g < T \leq 6 \end{cases}$$  \hspace{1cm} (12)

Objective function$^{[19]}$

According to the need and with the need to control the response spectrum $S_n(T)(T = T_1 \ldots T_M)$ of the coordinate points $M$ and the allowable error $\varepsilon$ that response spectrum controls. The number of trigonometric series is $N$ determined by frequency increment. Internationally, $M = 40 - 60$ , $\varepsilon = 5 - 10\%$ , $N = 200 - 1000$. While occasionally $M$ and $N$ can reach about a hundred and several thousands$^{[20]}$. There should be a sufficient number of trigonometric series at each point of $T_i$, especially in the long period in which the response spectrum controls the coordinates. To prevent that the number of trigonometric series is too large to convergence, and make sure that it meets the above requirements, the coordinate points in long period can be encrypted and that in short period can be reduced so as to make the total coordinate points remain within the scope mention before .

2.5. Error Modification of Response Spectrum

The power spectrum formula and the response spectrum formula are approximate, and it is easy to produce large errors without iteration. Therefore, in order to meet the precision requirements, it is necessary for practical engineering applications to make iterative calculation. The relative error formula of iteration process is as follows:

$$R(T) = \left| \frac{S_n(T) - S^T_n(T)}{S^T_n} \right|$$  \hspace{1cm} (13)

where $S_n(T)$ is calculated response spectrum, and $S^T_n(T)$ is target response spectrum. when $R(t) > \varepsilon$ , there should be spectral correction and the correction factors formula are shown as follows:

$$S^{i+1}(\omega_k) = S'(\omega_k) \frac{S^T_n(\omega_k)}{S_n(\omega_k)}$$  \hspace{1cm} (14)

where $S^{i+1}(\omega_k)$ and $S'(\omega_k)$ are respectively the power spectrum of the $i+1$ and $i$ times iteration at the frequency point of $\omega_k$ and $S^T_n(\omega_k)$ and $S_n(\omega_k)$ are respectively the target spectrum value and calculated response spectrum value at the frequency point of $\omega_k$.

2.6. Engineering Case Analysis

A multi span continuous beam bridge is 378.92 meters long,10.5 meters broad. Its structural design benchmark period is 100 years, environmental category is category I, design safety level is the first class, and its peak acceleration of ground motion is 0.2g. According to the report provided by a project investigation center its site category is category III.
According to Seismic Code For Urban Bridge Design and Seismic ground motion parameter zonation map of china, $T_g$ is set as 0.55 seconds, and the maximum value $\eta_{2}\xi_{max}$ of design response spectrum for the frequent and rare earthquakes are 0.275g and 0.9g respectively. According to the above theories and methods, the exponential seismic wave and section seismic wave of envelop function are shown below. It can be seen from Fig.8 and Fig.9 that the allowable error of the acceleration response spectrum is less than 5%.

Figure 4. Waves of piecewise frequent earthquake

Figure 5. Waves of piecewise rare earthquake

Figure 6. Waves of exponential frequent earthquake

Figure 7. Waves of exponential rare earthquake

Figure 8. Artificial response spectrum and design response spectrum under E1 modification

Figure 9. Artificial response spectrum and design response spectrum under E2 modification

3. Seismic Time-History Analysis and Frequency Domain Analysis

3.1. The Acceleration Amplitude Spectrum of Seismic Waves

When the external load frequency is equal to or close to the natural vibration frequency of the structure, it will cause sympathetic vibration and increase the response of the structure and even cause the damage of the structure. In the field of seismic engineering, the external load is mainly ground
motion, so the frequency of seismic time history is very important for engineering seismic resistance. The seismic time history is a complicated function changing with the time and does not directly reflect frequency. But the Fourier Principle indicates that any continuous timings and signals can be expressed as the superposition of infinite sine wave signals of different frequency. According to Fourier Transform Algorithm, the original signals which are directly measured is used to calculate the frequency, amplitude and phase of the different sine or cosine wave signals in a cumulative way. Fourier Transform Algorithm can transform the complex time domain signals into frequency domain signals which are easy to analyze. Seismic acceleration is composed of discrete points and can be transformed in Fourier Transform Algorithm as follows:

\[
A(n_{-1}, n_{-2}, \ldots, n_{0}) = \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} \left[ p_{n}(m_{-1}, m_{-2}, \ldots, m_{0}) \times W_{n}^{-\frac{n m}{2}} \times W_{m}^{-\frac{m n}{2}} \times \ldots \times W_{N}^{-\frac{n m}{2}} \right]
\]

where \( A(n_{-1}, n_{-2}, \ldots, n_{0}) \) is the result of Fast Fourier Transform, \( N \) is discrete sequence number. The formula of parameter relations is given as follows:

\[
\begin{align*}
N &= 2^{\gamma} \\
n &= 2^{\gamma-1} n_{-1} + 2^{\gamma-2} n_{-2} + \cdots + n_{0} \\
m &= 2^{\gamma-1} m_{-1} + 2^{\gamma-2} m_{-2} + \cdots + m_{0} \\
W_{n} &= \exp(-j2\pi N)
\end{align*}
\]

where \( \gamma \) is an integer, each value of \( n \) and \( m \) is within the range of 0 to \( N - 1 \), which can be expressed as a binary coefficient, each of which has a binary coefficient of 1 or 0, depending on the actual values of \( n \) and \( m \). The spectrum map of acceleration amplitude can be obtained by Fourier Transform.

![Figure 10. Acceleration amplitude spectrum of piecewise frequent earthquake](image)

![Figure 11. Acceleration amplitude spectrum of piecewise rare earthquake](image)

![Figure 12. Acceleration amplitude spectrum of exponential frequent earthquake](image)

![Figure 13. Acceleration amplitude spectrum of exponential rare earthquake](image)

From Fig.10 to Fig.13, it is can be seen that the amplitude of each frequency is less than that of the time history acceleration. The main frequency of seismic time history distributes within the range of 0-
10Hz, and the amplitude of acceleration is the largest when the frequency is near 2Hz, so the value of $\omega_k$ is the largest when the value of $C_k$ is about $4\pi$. Under the same condition of acceleration design spectrum, the maximum value of the acceleration amplitude spectrum of the seismic acceleration time histories of different envelope functions is approximated, which demonstrates that envelop function does not affect the extreme value of acceleration amplitude spectrum. Under the condition that the envelop function is the same and the acceleration design spectrum is different, the maximum values of the acceleration amplitude spectrum differs the most. It is inferred that the main factor affecting the amplitude spectrum of acceleration is the acceleration design spectrum.

3.2. Energy Spectrum Density of Seismic Waves

Fourier amplitude spectrum of the square is called the power spectral density, which describes the distribution of frequency domain signal energy as follows:

$$
\int_{-\infty}^{\infty} \left| f(t) \right|^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left| F(\omega) \right|^2 d\omega
$$

where $|F(\omega)|^2$ is the energy spectrum density.

The acquisition interval time of seismic time history is 0.02 seconds, the sampling frequency is 50 HZ, so the frequency range is 0-50HZ. Nyquist frequency is calculated as 25HZ. When the frequency is more than Nyquist frequency, the graph has positive symmetry. Therefore the frequency range of this paper is 0-25Hz. The energy spectrum density of artificial acceleration is as follows:

![Energy spectrum density of piecewise frequent earthquake](image1)

![Energy spectrum density of piecewise rare earthquake](image2)

![Energy spectrum density of exponential frequent earthquake](image3)

![Energy spectrum density of exponential rare earthquake](image4)

Fig.14 to Fig.17 shows that the energy is mainly distributed within the range of 0-5Hz and that when the frequency is in the vicinity of 2Hz the energy density reaches the maximum value, which indicates that a cosine function of the frequency of earthquake acceleration is mainly distributed within the range of 0-5Hz, and 2HZ about is the main region where cosine function frequency
distributes. Under the same condition of acceleration design spectrum, the difference between the maximum value of the energy spectrum density of the acceleration time history of different envelope functions is the most significant. That shows that the form of envelop functions is the main factor affecting the density of energy spectrum.

4. Generalized Power

4.1. Definition of Generalized Power

The seismic acceleration data obtained by the synthetic seismic acceleration time history function has the same three stages of rising, stationary and drooping as the measured time history acceleration data. As a result, the total seismic energy is limited. As the artificial earthquake wave is a superposition of several cosine functions, and each cosine function satisfies absolute value integral convergence, and according to the integral linear properties, seismic wave function also satisfies the integral absolute value of convergence. Within a cycle, artificial wave function does not have discontinous points and has finite maximums and minimums, so the artificial wave function meets Dirichlet condition. The absolute value of artificial wave function on infinite interval has integral convergence. The two properties of the artificial wave function determine that it satisfies the continuous energy integral equation, and also satisfies the discrete energy integral equation. Discrete energy integral equation is shown below:

\[
\sum_{n=0}^{N-1} [x(n)]^2 = \frac{1}{N} \sum_{k=0}^{N-1} |X(k)|^2
\]  

(18)

\[
\Delta t = \frac{T_p}{N}
\]  

(19)

\[
T_p = \frac{1}{f}\n\]  

(20)

Make equivalent substitution on the two equations above can obtain the equation as follows:

\[
\Delta t = \frac{1}{N\Delta f}
\]  

(21)

Multiplying the two ends of the equation by \(\Delta t\) can obtain the equation as follows:

\[
\sum_{n=0}^{N-1} [x(n)]^2 \Delta t = \frac{1}{N\Delta f} \sum_{k=0}^{N-1} |X(k)|^2
\]

(22)

where \(x(n)\) is the discrete numerical value of seismic time history, \(T_p\) is the duration time, \(N\) is the number of discretions, \(X(k)\) is Fourier transform, \(\Delta t\) is the intervals of recording seismic acceleration, \(\Delta f\) is the spectral resolution. Equation22 is the calculation formula of generalized power.

4.2. Calculation of Generalized Power

The generalized power of all types of seismic acceleration can be obtained form the formula above, as shown below:

| Type of acceleration     | Piecewise frequent earthquake (m²s⁻¹) | Exponential frequent earthquake (m²s⁻¹) | Piecewise rare earthquake (m²s⁻¹) | Exponential rare earthquake (m²s⁻¹) |
|--------------------------|--------------------------------------|----------------------------------------|----------------------------------|------------------------------------|
| Generalized power        | 2.79                                 | 2.06                                   | 29.93                            | 23.66                              |

It can be seen from Table2 that the percentage of difference between the frequent earthquakes whose envelope function is piecewise function and those whose envelope function is exponential
function is 26.16%. And the percentage of difference between the rare earthquakes whose envelope function is piecewise function and those whose envelope function is exponential function is 20.95%. The acceleration response spectrum of frequent earthquakes and that of rare earthquakes is the same. The energy density spectrums of the two types of earthquake are similar. The envelope functions of them are different. And the duration time of them is identical. It can be concluded that envelope function has influences on generalized power. Envelope function has a longer stationary segment, which makes the generalized power of piecewise function bigger than that of the exponential function under the same conditions.

5. Conclusion
(1) The purpose of artificial seismic acceleration is to synthesize artificial earthquakes that are statistically significant or similar to potential future earthquakes. Through the fitting of triangular series method and the correction iteration of the initial wave, the artificial earthquake time-history which satisfies the engineering precision and engineering needs can be obtained.

(2) Based on the frequency domain transformation of artificial earthquake time-history, the main frequency can be obtained, which can provide reference for the natural frequency design of structures. The seismic acceleration amplitude spectrum and the energy spectral density reflect the frequency characteristics of the artificial earthquake time-history, which is consistent with the spectral characteristics of the real seismic wave. Therefore, the aspect of spectrum also shows the rationality and feasibility of the artificial earthquake time-history in place of the ground motion. The main factors influencing the acceleration amplitude spectrum and the energy spectrum density are the acceleration design spectrum and the envelope function respectively.

(3) The future earthquake time-history is a random timing, but once the earthquake time-history happens, it is a determined timing, so the power spectrum density can be used to simulate the future earthquake time-history and the energy spectrum can be used when the earthquake time-history is determined. The formula derived from the discrete Parseval energy integral has a clear physical meaning. This energy is the average meaning of energy and is called generalized power. It is a comprehensive measurement of the seismic wave acceleration and the fullness of the waveform, which makes it possible to study the seismic wave and seismic energy from the aspect of energy. The generalized power is only suitable for acceleration, and the generalized power has the same unit as the acceleration power spectral density, but their physical meanings are different. According to the similarity between artificial seismic wave and natural seismic wave, generalized power can also be applied to the analysis of natural seismic wave.

References
[1] Kang Y G, Chang Y Z, Xu T, et al 2013 Dynamic stability analysis of steel-concrete composite ribbed shell (Trans Tech Publications) vol 712 pp822-26.
[2] Levy S and Wilkinson J P D 1976 Generation of artificial time-histories rich in all frequencies from given response spectra J. Nuclear Engineering and Design, 38(2) 241-51
[3] Vanmarcke E H 1976 Structural response to earthquakes J. Seismic risk and engineering decisions 287-337
[4] Tsai N C 1972 Spectrum-compatible motions for design purposes J. Journal of the Engineering Mechanics Division 98(2) 345-356
[5] Kost G, Tellkamp T, Kamil H 1978 Automated generation of spectrum-compatible artificial time histories J. Nuclear Engineering and Design 45(1) 243-49
[6] Aziz T S and Biswas J K 1979 Spectrum-compatible time histories for seismic design of nuclear power plants J. Journal of Earthquake Engineering 301-24.
[7] Shin G and Song O 2016 A Time-Domain Method to Generate Artificial Time History from a Given Reference Response Spectrum J. Nuclear Engineering and Technology 48(3) 831-39
[8] Kang P, Wang Z, Sun J 2014 Generation of artificial earthquakes for matching target response unsmooth spectrum via wavelet package transform J. Transactions of Nonferrous Metals Society of China 24(8) 2612-17
[9] Zhao F, Zhang Y, Lü H 2006 Artificial ground motion compatible with specified ground shaking peaks and target response spectrum J. Earthquake Engineering and Engineering Vibration 5 41-8
[10] Gao Y F and Zhang J 2007 Study on seismic hazard analysis (Beijing: Science Press)
[11] Li J and Li G Q 1992 Introduction to seismic engineering (Beijing: Earthquake Press)
[12] Jiang Z R and Hong F 1984 Conversion of Power Spectrum and Response Spectrum and Artificial Seismic Wave J. Journal of Seismic Engineering and Engineering Vibration 4 (3) 1-11
[13] Hu Y X and Zhou X Y 1962 Reaction of Elastic System in Smooth and Smooth Ground Motion: Seismic Engineering Research Report (Part 1) (Beijing: Science Press)
[14] Iyengar R N and Iyengar K T S R 1969 A nonstationary random process model for earthquake accelerograms J. Bulletin of the Seismological Society of America 59(3) 1163-88
[15] Wang G Y 2006 Structural dynamics (Beijing: Higher Education Press)
[16] Hu X X, Zhang L J, Hua H L 2006 Artificial Ground Motion Synthesis Based on Regulating Response Spectrum (Hohai University) pp123-28
[17] Chen Y Q, Liu X G, Gong S L1981 Artificial seismic waves fitted to standard response spectra J. Journal of Building Structures 2 (4) 34-42
[18] Huo J R 1989 Study on Attenuation Law of Near Field Strong Ground Motion (Harbin: Institute of Engineering Mechanics China Earthquake Administration)
[19] 2011 C J J. Code for Seismic Design of Urban Bridges [S].2011
[20] Hu Y X 2006 Earthquake Engineering (Beijing: Earthquake Press)
[21] Zhang Y L 2012 Integral transformation (Beijing: Higher Education Press)
[22] Cheng P Q 2015 Design of digital signal processing (Beijing: Tsinghua University Press)