Artificial Ground Motion Input Based on Structural Dynamic Compatibility

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Abstract. The artificial ground motion input currently used is arbitrary and uncertain. It can only consider basic elements such as magnitude and preliminarily estimated epicenter distance. This is in sharp contrast with the increasingly accurate calculation of structural seismic response. It is a bottleneck for the further refinement of ground motion research. In order to solve this problem, an artificial ground motion input mode compatible with the dynamic characteristics of the target structure is constructed. It can greatly improve the safety of the building in the architectural design stage without increasing the cost excessively. Obviously, the model is more targeted, safe and reasonable.

Keywords. Dynamic characteristics, compatibility, artificial ground motion, earthquake response, envelope.

1. Introduction
A large number of related researches on seismic records and ground motion show that earthquake motion is not accurately predictable and repeatable [1]. Therefore, in the generation of artificial ground motion, it is very difficult to accurately predict or simulate the possible future earthquake motion forms, no matter how fully considering the site characteristics. The reason is that the occurrence of ground motion is usually a very complex random process. The details of this process often depend on the source rupture mode, the accurate rupture location on the active fault, the propagation path of seismic wave when the rupture occurs, and the influence of local site conditions. Because of the complexity and variability of these factors themselves, they can't be accurately simulated in the generation of artificial ground motion. At present, only two basic factors such as magnitude and epicenter distance can be considered.

However, this artificial ground motion generation method, which can only symbolically consider one or two simple elements existing in the actual ground motion, is far from meeting the needs of seismic safety analysis. The relatively rough synthesis method will lead to a huge difference between the actual natural ground motion and the artificial synthetic ground motion. This difference leads to the incompatibility between the more accurate artificial ground motion response analysis and the more rough artificial ground motion generation, which makes the problem of artificial ground motion generation become the bottleneck restricting the breakthrough of modern seismic research. Therefore, it is an important research direction how to break through the bottleneck and overcome the uncertainties in the generation of artificial ground motion under the premise of fully understanding the inexact prediction of natural ground motion. Then, a targeted and compatible artificial ground motion time history is generated to ensure the safety and effectiveness of the structure within the active and
controllable probability range, no matter what the future ground motion form is, as long as it falls within the corresponding seismic fortification level range, it will become an important artificial ground motion input mode. It has a wide range of social practical and economic value, providing more practical protection for people's life and property.

2. Establish the Artificial Ground Motion Model Compatible with the Dynamic Characteristics of the Structure

The model includes the important dynamic characteristics of the target structure, including the energy distribution of the dominant narrow frequency component related to the natural frequency of the target structure, and the total energy input matching the seismic fortification level of the structure. The establishment of the power spectrum model of the target solves the important problems such as the distribution of the total energy and the energy standard carried by the dominant time-frequency components in the generation of artificial ground motion, and provides a more reasonable input mode for the response research of the structure under earthquake.

2.1. Formatting the Title

The ground motion model of frequency domain modulation method is Fourier spectrum model, which mainly includes two aspects: the construction of Fourier amplitude spectrum model [2] and phase spectrum model [3].

When establishing the amplitude spectrum, the energy distribution mode of power spectrum matrix is used to consider the distribution and attenuation form of ground motion energy in each particle in space. At the same time, the spatial correlation of motion coupling of each particle is fully considered. When the power spectrum matrix is used for energy distribution, local site conditions such as epicenter distance, earthquake incidence angle and soil layer thickness are fully taken into account, so that the overall energy is basically consistent with the real local seismic intensity, and the local energy of each particle has reasonable spatial correlation.

In order to obtain the time history curve of ground motion, the spatial correlation ground motion composition equation is established, as shown in equation (1).

\[
F_m(\omega_j) = \sum_{r=1}^{N} \sqrt{\Delta \omega} \cdot L_{mr}(\omega_j) \cdot e^{i(\phi_j(\omega_j) - \phi_r(\omega_j))} 
\]

among them, \(\omega_j\) represents frequency, \(\omega_j\) is the discrete value of frequency, \(F_m(\omega_j)\) is Fourier spectra of mass point m, it changes with frequency \(\omega_j\). \(\Delta \omega\) represents the step size of the frequency, \(L_{mr}(\omega_j)\) is the element corresponding to the m-th row and r-th column in the \(N \times N\) matrix obtained after the square root decomposition of the power spectrum matrix. \(\phi_j(\omega_j)\) is the phase angle of space-related ground motion, in this paper, conditional simulation is used, that is, the corresponding phase information is extracted from the natural ground motion to assign the phase angle. \(d_r - d_m\) is the reflection factor of the traveling wave effect, where \(d_r\) and \(d_m\) are the coordinates of point r and point m, respectively, \(v_a(\omega_j)\) is the apparent wave speed, and \(\omega_j\) is the discrete value of frequency as mentioned above.

The Fourier spectrum of any particle m can be obtained by the above ground motion model. After the inverse Fourier transform, the time history curve of spatial correlation ground motion of m point can be obtained.

2.2. Fitting of Compatibility with Structural Dynamic Characteristics

In this paper, the wavelet decomposition and reconstruction method is used to realize the compatibility fitting of the dynamic characteristics of the target structure in the reconstruction process. After the
initial ground motion is synthesized by using the model in 1.1, the initial seismic signal is decomposed by wavelet to form n-order signal components. Each signal component contains only a narrow band, which can be approximate to a central frequency point. Then, according to the actual site characteristics and the dynamic characteristics of the target structure, the weight coefficient of any frequency band can be adjusted freely. The weight coefficient determines the content of the frequency component. Finally, by combining and reconstructing the weight coefficients, the ideal input waveforms with different compatibility with the target structure can be generated. The adjustment process and main steps are as follows:

2.2.1. Wavelet Decomposition. For the continuous wavelet transform of any function, the expression [4]

\[
W_{a,b}(f(t)) = \int_{-\infty}^{\infty} f(t) \psi_{a,b}(t) \, dt
\]

among them, \( \psi_{a,b}(t) \) is the conjugate of \( \psi_{a,b}(t) \); and \( \psi_{a,b}^{*}(t) = \frac{1}{\sqrt{a}} \psi_{a,b}(\frac{t-b}{a}) \).

suppose \( f(t) = f(k\Delta t), \quad t \in (k+1) \), then

\[
W_{a,b}(f(t)) = \sum_{k} f(k\Delta t) \psi_{a,b}^{*}(k\Delta t) \Delta t
\]

In the above process, the continuous wavelet transform is transformed into discrete form to facilitate programming calculation.

The above calculation process can be summarized as follows:
(1) A wavelet function which is close to the original signal is selected to form the wavelet analysis together with the corresponding scale function;
(2) The selected wavelet with different scales (a short band with different vibration frequencies) is compared with the original signal, and a series of wavelet coefficients \( C \) under different scales are obtained. The value of \( C \) represents the similarity between the short band of this scale (frequency) and the original signal.
(3) Parameter \( B \) is a stationary parameter. The position of the segment to be analyzed in the original signal is moved by increasing \( B \). with the increase of \( B \), the wavelet continuously moves to the right until the whole signal is analyzed.

2.2.2. Selective Reconstruction. Suppose the frequency domain interval to be reconstructed is \( [\omega_1, \omega_2] \), then the integral of \( X(a) \) in interval \( [a_1, a_2] \) can be expressed as

\[
\int_{a_1}^{a_2} X(a) \, da = \int_{\omega_1}^{\omega_2} S(\omega) \Phi(\omega,m) \, dm = S(\omega) \int_{\omega_1}^{\omega_2} \Phi(\omega,m) \, dm
\]

In order to reconstruct the seismic signal in the frequency range \( [\omega_1, \omega_2] \), construct a function

\[
h(\omega) = S(\omega) \int_{\omega_1}^{\omega_2} C(\omega) \Phi(\omega,m) \, dm
\]

Discretize \( C(m) \) on the interval \( [\omega_1, \omega_2] \), then
\[ h(\omega) = S(\omega) \sum_{i=1}^{N} C(m_i) \Phi(\omega, m_i) \]  

Among them, \( m_i \in [\omega_1, \omega_2] \) and \( C(m_i) \) are coefficients that change with frequency, called reconstruction coefficients. Then do the inverse Fourier transform of \( h(\omega) \), there is

\[ F(t) = (h(\omega), e^{-i\omega t}) = \frac{1}{2\pi} \int_{-\infty}^{\infty} h(\omega), e^{i\omega t} \, d\omega \]  

Take the real part \( F(t) \) of \( F(t) \) to get the time-domain seismic signal component reconstructed in the corresponding frequency band. In the above signal reconstruction process, the \( h(\omega) = S(\omega) \sum_{i=1}^{N} C(m_i) \Phi(\omega, m_i) \) expression is constantly adjusted, and then combined, signals that meet different characteristics and different similarities can be obtained.

2.2.3. Explicit equation for frequency adjustment. For any \( f(t) \in L^2(R) \), suppose there is \( \{C^0_n\}_{n \in \mathbb{Z}} \in \ell^2 \) such that \( f(t) = \sum_{n \in \mathbb{Z}} C^0_n \phi_n(t) \), then the wavelet decomposition and reconstruction algorithm is as follows

(1) Decomposition algorithm

\[ C^j_n = 2^{-j/2} \sum_{k \in \mathbb{Z}} h_{2^j-k} C^j_k \]  
\[ D^j_n = 2^{-j/2} \sum_{k \in \mathbb{Z}} g_{2^j-k} C^j_k \]  

(2) Reconstruction algorithm

\[ C^j_n = \sum_{k \in \mathbb{Z}} h_{2^j-k} C^j_k + \sum_{k \in \mathbb{Z}} g_{2^j-k} C^j_k \]  

(3) Decomposed and reconstructed ground motion time history expression

\[ f = \sum_{k \in \mathbb{Z}} a^j_k \phi(2^{j-1} x - k) + \sum_{k \in \mathbb{Z}} b^j_k \psi(2^{j-1} x - k) \]  

In the above calculation, \( C^j_n \) is the low-frequency wavelet coefficient, \( D^j_n \) is the high-frequency wavelet coefficient; \( h_{2^j-k} \) is the low-pass filter, and \( g_{2^j-k} \) is the high-pass filter; \( j \) is the order of the wavelet coefficient, the higher the order, the greater the decomposed ground motion component. The higher the frequency, \( \phi(2^{j-1} x - k) \) is the scaling function, and \( \psi(2^{j-1} x - k) \) is the wavelet function.

2.3. Fitting of Compatibility with Structural Dynamic Characteristics

After the generation of the target power spectrum model, the generated ground motion time history is combined with the dynamic response characteristics of the target structure to a certain extent. However, in order to ensure that the generated ground motion mileage has the envelope (safety level) required by the designer, in addition to fitting the initial ground motion time history with the design response spectrum, it also matches with the target structure several times. The envelope of the
response time history curve under the earthquake input is fitted to ensure the envelope of the fitted time history.

2.3.1. Fitting with Target Response Spectrum. When fitting the target response spectrum, we need to determine the design life of the target response spectrum and the probability of exceeding the design life. There are two common types of exceeding probability: 10% in 50 years and 5% in 100 years, which can be selected according to the importance of the structure and different seismic requirements.

2.3.2. Fitting with Target Envelope. The objective envelope is the objective envelope function of the time history curve of the seismic response of the structure under several ground motion inputs. Therefore, this project needs to design the objective envelope function first, and make it envelope to the extreme response of other ground motion input.

When the initial ground motion time history is fitted and iterated with the target response spectrum according to 1.3.1, it is input into the structure, and the seismic response time history curve of the structure under the input is obtained from the motion equation. By calculating the difference vector between the response curve and the design objective envelope function, the time history increment of seismic input is inversely calculated, and the increment is superimposed on the seismic time history curve, and then the target is repeated. The standard response spectrum is fitted, and then it is fitted with the target envelope in 1.3.2 of this step. The envelope wave pattern satisfying the double fitting conditions is finally obtained through repeated iterations. The calculation process is as follows:

First calculate the first N-order natural frequencies of the target structure (usually the first 3 orders), and find the energy distribution coefficient $\zeta_i \ (i=1,2,...K)$ of the dominant time-frequency component corresponding to each natural frequency in the power spectrum set. The number of K samples, usually larger), after sorting by value, N K-order high-dimensional vectors $\zeta_k$ composed of energy distribution coefficients can be formed, through Monte Carlo statistical variance regression analysis [5] and beyond probability calculations, Choose an appropriate interpolation value in each high-dimensional vector to ensure that the outlier part of each interpolation value satisfies a certain transcendental probability $\beta_i$.

When the transcendence probability of the energy distribution coefficient $\zeta_i$ of each order of superior time-frequency component $\beta_1, \beta_2, \beta_3, ..., \beta_N$ is calculated, the envelope degree of the envelope waveform constitutes the joint probability distribution function, which can be Calculate it according to the function $W=(1-\beta_1)\times(1-\beta_2)\times(1-\beta_3)\times...\times(1-\beta_N)$.

Among them, the probability of transcendence $\beta_1, \beta_2, \beta_3,..., \beta_N$ constitutes an N-dimensional interpolation vector. If the above process is repeated M times, M N-dimensional vectors can be obtained, and M corresponding envelopes can be calculated Degree value, its calculation mode is as follows:

$$Q=L\times W\times 1\times(1-P)(1-\beta_1)(1-\beta_2)(1-\beta_3)...(1-\beta_n)$$

(Among them, L is the sample size inclusion probability of the initial wave, W is the joint distribution probability, P is the exceedance probability of the initial capacity, $\beta_1, \beta_2, \beta_3, ..., \beta_n$ are the coupling coefficients of the dominant time-frequency components of each order Beyond probability.)

In addition to the dominant time-frequency components calculated above, there may be some potential "dominant time-frequency component families" in the long-period period of bedrock ground motion. The center frequency of this family of components is very close to the fundamental frequency of the structure or a low-order natural frequency. However, due to the low energy and small amplitude carried by this narrow frequency band in the bedrock ground motion time history, the statistical time is very convenient easy to ignore. It should be noted that the energy carried by this frequency band will be greatly enhanced after being filtered and amplified by the overlying soil layer, thus forming a "dominant frequency family" which is very close to the fundamental frequency of the structure or a low-order natural frequency. Because this frequency family is very easy to cause resonance like
response of the structure, it is very destructive. Therefore, this part of energy should be accurately reflected by the forward algorithm of vertical strata, and the sample containment should be as close as possible to 1. Therefore, in the above calculation, the constant "1" should be approximately taken.

When the above envelope calculation value $Q$ is equal to the target envelope degree $Q_0$, the energy distribution coefficient value $\zeta$ of each order dominant time-frequency component is the calculated energy distribution probability density; when $Q \leq Q_0$, the above interpolation calculation is continued, and different transcendence probabilities are selected according to fixed step size and different orders, and the above calculation is repeated until $q = Q_0$ is satisfied.

3. Large Scale Shaking Table Test

In order to verify the safety and envelopment of artificial ground motion compatible with the dynamic characteristics of the structure, a 29 floors high-rise frame core tube structure (90m high, with pile raft foundation) is taken as the research object in this test. The geometric similarity ratio of prototype and model is 100:1. In order to accurately simulate the first three natural frequencies of prototype structure, the model adopts a multi degree of freedom system with three free particles, and the natural frequency similarity ratio is accurately restored as 1:1. The size of the model box is $2 \times 1.5 \times 1.5$ m. The material similarity ratio and contact similarity ratio between prototype and model are designed according to the separation dimension similarity theory. The interface between soil and structure contains a layer of affinity similar material, which is affinity material + wood structure model. The elastic modulus of wood structure is 6 Mpa.

After the construction of the test model, the envelope wave type, natural ground motion time history and traditional artificial ground motion time history can be input in turn to test the dynamic response under various input conditions. Then, according to the envelopment criterion [6], the envelope degree of seismic response amplitude under enveloping wave type input to other input responses can be determined, and the Finally, the envelope value is compared with the target envelope to complete the envelope test and verification.

3.1. Purpose of the Experiment

The envelope of the artificial ground motion compatible with the dynamic characteristics of the structure is verified.

3.2. Working Condition Selection

Firstly, the natural vibration period and frequency of the structure model are calculated through the natural vibration experiment, and the center frequency of artificial ground motion input is continuously adjusted to make the center frequency fluctuate near the natural frequency of the target structure. After testing, the natural vibration period of the structure model is 2 Hz, and the center frequency of artificial ground motion input is 2 Hz, 0.3 Hz, 1 Hz, 1.5 Hz, 5 Hz. The test design conditions are shown in table 1.

| Wave pattern | Center frequency | Bandwidth |
|--------------|------------------|-----------|
| wave1        | 2Hz              | 2Hz       |
| wave2        | 2Hz              | 1Hz       |
| wave3        | 2Hz              | 0.5Hz     |
| wave4        | 2Hz              | pulse     |
| wave5        | 0.3Hz            | 0.5Hz     |
| wave6        | 1Hz              | 0.5Hz     |
| wave7        | 1.5Hz            | 0.5Hz     |
| wave8        | 5Hz              | 0.5Hz     |
There are four types of waveforms used in the experiment: white noise, artificial wave, sine wave and smoothing wave. The amplitude of white noise is 0.05 g, and the amplitude of artificial wave, sine wave and screen clearing wave is 0.1 g, 0.3 g, 0.5 g, 0.9 g, and the duration is 140 s.

### 3.3. Experimental Model Making and Shaking Table Model Box Design

The large-scale two-way vibration table of MTS company purchased by Hainan University structural engineering test center is used as the test loading equipment, as shown in figure 1. The size of shaking table is 3 m × 3 m, the maximum specimen weight is 20 t, the maximum overturning moment is 30 t · m, the maximum torsion force is 10 t · m, the working frequency range is 0 ~ 50 Hz, the maximum acceleration of the table top with full load is ± 1.1 g in X direction (longitudinal direction) ± 1.1 g in Y direction (transverse direction), and the vibration waveform is periodic wave, random wave and seismic wave. The test data acquisition system is 64 channels.

![Figure 1. Shaking table equipment.](image1)

![Figure 2. Model box.](image2)

The external dimension of the model box for the test is 200 cm (length) × 150 cm (width) × 160 cm (height), and the material is steel plate. The detailed style is shown in figure 2. The four sides of the box wall are welded by electric welding, and the outer side is reinforced by channel steel. The model and the shaking table are connected by bolts.

### 3.4. Sensor Connection

The main sensors used in the test are wire displacement meter, accelerometer and strain gauge. The layout of each sensor is shown in figure 3.

![Figure 3. Sensor layout of model structure.](image3)
4. Sections, Subsections and Subsubsections

4.1. Acceleration Output
The three output forms (black, green and red) in figure 4 correspond to three input waveforms with envelope degree of 75%, 85% and 95%. The black acceleration response time history has the smallest amplitude, the red acceleration response time history has the largest amplitude, and the green acceleration response time history amplitude is between the two. Therefore, the larger the envelope degree of ground motion input is, the stronger the seismic acceleration response is.

Figure 4. Acceleration output.

4.2. Displacement Output
The three output forms (red, blue and green) in figure 5 correspond to three input modes with envelope degree of 75%, 85% and 95%. Among them, the amplitude of red displacement response time history is the smallest, the amplitude of green displacement response time history is the largest, and the amplitude of blue plus displacement response time history is between the two. Therefore, the larger the envelope degree of the ground motion input is, the stronger the displacement seismic response of the structure is.

Figure 5. Displacement output.
4.3. Earth Pressure Output
The three output forms (from top to bottom) in figure 6 correspond to three input waveforms with envelope degree of 75%, 85% and 95%. The amplitude of the first earth pressure output time history is the smallest, the second one is the largest, and the amplitude of the last earth pressure output time history is between the two. This output result is different from the theoretical analysis (because in theory, it should be increased from top to bottom). This may be due to the partial loosening of the contact surface between the earth pressure gauge and the soil in the process of vibration during the continuous test, resulting in the earth pressure in the third stage can not be transmitted completely and accurately. On this point, we will further explore in the follow-up experiments.

4.4. Strain output
The three output forms (black, green and red) in figure 7 correspond to three input wave types with envelope degree of 75%, 85% and 95%. Among them, the black strain response time history has the smallest amplitude, the red strain response time history has the largest amplitude, and the green response time history amplitude is between the two. Therefore, the larger the envelope degree of ground motion input, the stronger the seismic response.
4.5. Strain Output

4.5.1. Spectrum energy analysis. Using HHT transform [7] and wavelet energy analysis method [8-9], the energy distribution of the above three input forms is obtained as follows:

![Figure 8. Input energy distribution of ground motion with envelope degree of 75%.](image)

![Figure 9. Input energy distribution of ground motion with 85% envelope.](image)

![Figure 10. Input energy distribution of ground motion with 95% envelope degree.](image)

It can be seen from figures 8, 9 and 10 above that the output energy tends to be amplified, which indicates that the greater the dynamic compatibility with the target structure, the easier it is to obtain energy in vibration, and there is a certain (degree controllable) energy absorption effect.

4.5.2. Envelope Analysis (Envelope of Structural Response). In figure 11, the center frequency of response time history 3 is 2 Hz, that of reaction time history 2 is 1.5 Hz, and that of reaction time history 1 is 0.5 Hz. Since the natural vibration frequency of structure is 2 Hz, the dynamic characteristic value of time history 3 is closest to the target structure, followed by time history 2; the difference between time history 1 and time history 1 is the largest.
Figure 11. Envelope analysis of different input sets (Same center frequency, different energy concentration).

Figure 12. Envelope analysis of different center frequency inputs (Same bandwidth, different center frequencies).

Figure 13. Envelope analysis with double offset input (Different energy distribution, different center frequency, but the best dynamic compatibility with the target structure).

In Figure 12, the center frequency of the three input time histories of ground motion response is 3 Hz, but the bandwidth of time history 3 is 0.5 Hz, the bandwidth of time history 2 is 1 Hz, and the bandwidth of time history 1 is 2 Hz. It can be seen that the smaller the bandwidth is, the stronger the energy response is, and the center frequency is concentrated.

In Figure 13, the center frequency of time course 3 is 2 Hz and the bandwidth is 0.5 Hz; the center frequency of time course 2 is 1.5 Hz and the bandwidth is 1 Hz; the center frequency of time course 1 is 0.5 Hz and the bandwidth is 2 Hz. Therefore, the center frequency of time course 3 is the closest to the target structure, and the energy is the most concentrated; time course 2 is the second, and the center frequency of time course 1 is the farthest from the target structure, and the energy distribution is not concentrated enough.

However, it can be seen that the higher the seismic envelope map is, the better the structural response is.

5. Conclusion
Through the large-scale shaking table test, the conclusions are as follows:

1) In the seismic response, the target structure is sensitive to the dominant frequency component close to the natural frequency, and the amplification effect of ground motion is obvious;

2) When the energy carried by dominant frequency is constant, the wider the bandwidth is, the smaller the peak acceleration response of the target structure is;
3) The response intensity of the target structure to envelope artificial ground motion exceeds the natural ground motion with the same amplitude;

4) With the difference of envelope, the time history of structural response will change. The specific trend is that the greater the envelope degree, the stronger the seismic response;

5) In contrast, the artificial ground motion input compatible with the dynamic characteristics of the structure has envelope, which can reflect the most unfavorable earthquake input of the structure under a certain probability, so it is more secure. However, the peak value of the structural response under the seismic input is not much different from other input forms. Therefore, the seismic form will not increase the seismic cost of buildings excessively, but will expose some weak parts of the target structure more comprehensively, so as to take more comprehensive measures to improve seismic capacity in advance.

6) The results of this study need to be further refined and in-depth. For example, when selecting artificial ground motion input for the target building, how much envelope is economic and reasonable, and how to accurately evaluate the envelope degree and the probability of the actual occurrence of the earthquake in the site, etc., are expected to be carried out in the future research work.

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