TIME VARYING ARMA BASED STOCHASTIC SEISMIC MODEL

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ABSTRACT :
When the stochastic seismic response of the structures is studied, lots of the earthquake records fit for the selected site is needed to be used for initial data for structure model analysis. In the given site it does not always have the strong earthquake records, thus it's very important to make ideal model for description of realistic earthquake ground motion time history matching the location condition. In this paper we used the sample records reformed by Chinese code 2001 version for seismic design of buildings as target earthquake records and made a modified discrete time-vary ARMA model. Both amplitude and frequency nonstationarities were incorporated into the model. Chi-Square verification tests were performed on the different nonstationary ARMA model. Application of these verification procedures was discussed and showed that the proposed models were able to reflect accurately the nonstationary features on real earthquake accelerogram, both the time-variation of the frequency and amplitude content. Thus we made a more efficiently simulated earthquake records matching the site's condition are made and set up a organic connection between research and civil engineering design.

KEYWORDS:
time vary ARMA model; Box-Cox transform; nonstationarity; stochastic seismic model

The average process (process of ARMA) of autoregression glide is a good description of time-domain model of the steady random process, Jurkevics [1] and Chang [7]. First studied earthquake with the ARMA model. Since then, many studies have been done using this approach [2-4]. Because of using discrete difference equation to express motion equations of the filter, this model has been shown to be superior to the continuous model in numerical computation and theoretical analysis. In addition, this model could describe seismic process better than that general and lower order ARMA processes, such as ARMA(2.1) and ARMA(4.1) did. Conte and coworkers [4] pointed out that the linear filter (including single filter and multiple filter) –based the model was the only one special case of lower order ARMA process. If choosing the parameter of AMRA properly, we may immediately make both of the two models be equivalent completely.

In our country, only a few studies on this model have been done. Hu Kongguo[5] and Li Yingmin'S[6] research all showed that the model had brighter development prospect. They simulated earthquake from goal response spectrum and studied the method of using the sequence of ARMA to synthesize artificial seismic wave.

As for using the ARMA model to simulate earthquake, lots of studies have been done abroad. , Three methods have been described specifically for handling nonstationarity seismic sequence. The first method is sectioning method; we considered that the sequence is steady in each small time-interval. Conte[9] divided six arrays into eight sections separately. Thus, we draw the conclusion that using low order ARMA model (ARMA(2.1),ARMA(4.1)) is more suitable. The second method is the one of intensity modulation that is developed by Ahmet S.Cakmak[11].It use Box- Cox transformation to solve the stationary status of abnormal distributed seismic wave, thus time variation-dependent ARMA model was set up, and relationship between time variation parameter and earthquake parameter could be expressed. The third one is that proposed by Conte JP[12].. In this method, ambulation window method and Carlman filtering method was adopted to build up time variation-dependent ARMA model. Time variation-dependent ARMA parameter and earthquake parameter could also be linked to each other. Mobarakeh etc. used Conte's time vary ARMA model to statistically analyze the data of seismic wave that happened in three different types of sites, especially in the property of frequency spectrum and showed that the model was able to match better with the record of initial seismic wave [12] .

Now we analyze the domestic and international method of using ARMA model in simulating earthquake. Domestic scholars inclined toward the engineering application, while the foreign scholars paid more attention to the theories of the seismic wave. The advantage of using response spectrum as[7,8] control objective of the model is to help the designer to use, but response spectrum can't reflect the influence of time delay and phase changing ,and it can't reflect the earthquake response of multiple-degree-of-freedom system. So adopting the original wave as control objective of analog wave reflects the randomness and the frequency spectrum property of the seismic wave better.

Analyzing the three methods of in time vary ARMA model mentioned above, wit seemed to us that he first one and the third one used time vary parameter model, while the second one used intensity modulation. ; In this paper, we combined Cakmak's time vary ARMA model [11]with that of Conte [12] organically, and put forward a new stochastic seismic model—modified time vary ARMA model, and demonstrated that our new model could simulate real seismic wave better than other ARMA models through real case study.

1. TIME VARY ARMA MODEL

If acceleration time series W'(t) of real seismic wave is taken as a sample, time-vary-parameter ARMA seismic model has the difference expression as follows:

$$W(t) = \phi_1(t)W(t-1) + \phi_2(t)W(t-2) + \ldots + \phi_p(t)W(t-p) + \sigma_e(t)\alpha_k(t) - \theta_1(t)\sigma_e(t-1)$$
$$\alpha(t-1) - \ldots - \theta_q(t)\sigma_e(t-q)\alpha(t-q) \quad (1)$$

In the formula: Φp(t) and θq(t), are respectively p-order autoregressive coefficient function and q-order moving average coefficient function which are corresponding to sample seismic wave W'(t); σe(t) is the standard deviation function of sample seismic wave W'(t); αe(t) is Gauss flat noise whose equalizing value is 0 and whose standard deviation is 1; W(t) is discrete process of simulating seismic acceleration, namely artificial wave. By changing random number seed only and then producing different Gauss flat noise αe(t), we substituted it to (1), then we could generate different artificial wave. The time vary model that was put forward in this paper adopts this model.

If Φ p(t), θ q(t) are constants, then that model will change into intensity modulation ARMA model, and its linear difference equation is as follows:

$$W_t = \phi_1 W_{t-1} + \phi_2 W_{t-2} + \ldots + \phi_p W_{t-p} + \sigma_e(t)\alpha_t - \theta_1\sigma_e(t-1)\alpha_{t-1} - \ldots - \theta_q\sigma_e(t-q)\alpha_{t-q} \quad (2)$$

In the formula: Φp、θq are p-order autoregressive coefficient and q-order moving average coefficient respectively; Wt is the process of artificial seismic acceleration; αk is Gauss flat noise whose equalizing value is 0.

If Φp (t)、θq(t) and σe(t) are all constants, then the model will transmute into the model of stationary random process—ARMA model, its linear difference equation is as follows:

$$W_t = \phi_1 W_{t-1} + \phi_2 W_{t-2} + \ldots + \phi_p W_{t-p} + \alpha_t - \theta_1\alpha_{t-1} - \ldots - \theta_q\alpha_{t-q} \quad (3)$$

In the formula: Φp、θq are p-order autoregressive coefficient and q-order moving average coefficient respectively; Wt is the process of artificial seismic acceleration; αk is Gauss flat noise whose equalizing value is 0.

2. The parameter assurance of modified time vary ARMA model

From the formula(1), we can know if we want to build up time vary ARMA seismic model, first we must define three functions: Φp(t)、θq(t) and σe(t).Its procedure is as follows:

1) setting up target wave W'(t); 2) Selecting of time vary ARMA model's order; 3) Estimating standard deviation function of target wave W'(t); 4) normalizing target wave; 5) carrying on parameter estimation of time vary ARMA model to normalized target wave W''(t) .

2.1 Building up the target wave

When selecting the seismic wave, we must consider three elements—amplitude value, time delay and frequency spectrum, but in real application, we select the seismic wave generally according to the type of chosen zone and protected intensity defined earthquake zoning, among them, the type of the soil in the zone is the key, it decides amplitude value and frequency spectrum property. In order to make the result have more universalities, we use EL-Centro acceleration wave.

There are many kinds of definitions about time delay[14], according to clause explanation of document[15]5.1.2, time delay is generally 5~10 times of structure base period.

We selects waveform data of the first 40 seconds in order to analyze it conveniently.

As for fetching amplitude value, selection of earthquake acceleration timing curve's maximum can be analyzed according to the time route in chart5.1.2-2 of document [15]. For example, Xi'an adopts eight-degree protection, taking designed basic earthquake acceleration as 0.2g, according to the regulation in document[15]5.1.2, the maximum of seismic wave amplitude that we used should be that after normalizing chosen seismic wave, we get a result, then let the result multiply the maximum in the blank above to obtain target wave.

2.2 The choice of the time vary ARMA model's order

In the formula(1), the choice of the ARMA model's order is a key problem, for steady ARMA series, we could adopt some adjudicating standard, such as FPE(the final forecast error standard), AIC(the red pond information standard), BIC(Bayes information standard) etc. [16], but for nonstationarity ARMA series, choosing its order is difficult, and the fundamental rule of choosing its order is AR's order which is twice of MA's order. Generally adopt the method of trial calculation, on the basis of the result's precision and calculated quantity etc., fix up the order. Therefore, we contrasted ARMA(2,1) and ARMA(4,2), and according to the analog result we determined the order of the model ultimately.

2.3 The estimate of standard deviation function

In the process of model establishment, it's a very important step to estimate sample seismic wave's standard deviation function σe(t). Underneath, we briefly described the process of building standard deviation function σe(t).

First we use weighted moving average method to estimate standard deviation σ'(t) and use Box-Cox transform to deal with it. The formula is as formula(4):

$$X_t = \begin{cases} \dfrac{(Z_t+\xi)^{\lambda}-1}{\lambda m_g^{\lambda-1}} & for\lambda \neq 0 \\ m_g \ln(Z_t+\xi) & for\lambda = 0 \end{cases} \tag{4}$$

In the formula, mg is a geometrical average: $m_g = \exp\left[\dfrac{\sum_{i=1}^{N}\ln(Z_i)}{N}\right]$, λis empirical value, N is the quantity of original data Zt , ξ is side-play amount.

Then, polynomial was fit with standard deviation function to get h(t). The fitted result (as formula (5)), was processed with Box-Cox transformation. Thus we obtained standard deviation function σe(t). It reflected dispersion degree of target wave, and its value influenced seriously amplitude value distribution of simulated wave that emerged in the end.

$$\sigma_e(t) = \begin{cases} [h(t)\lambda m_g + 1]^{\lambda-1} & for\lambda \neq 0 \\ \exp[h(t)/m_g] & for\lambda = 0 \end{cases} \tag{5}$$

In the formula above, parameters have the same meaning as formula (4).

2.4 Normalization of target seismic wave

We used the formula (6) to normalize target seismic wave W'.

$$W''(t) = \frac{(W'(t) - m)}{\sigma_e(t)} \tag{6}$$

In the formula: W'(t) a series of the target seismic wave; m is the average of the target wave; σe(t) is standard deviation function of the target wave.

2.5 Parameter estimation of time vary ARMA model

Time-moving window method(or call ambulation window method) can be used to estimate time vary ARMA model's parameters Φp(t)、θq(t). it is supposed that the sample series is always steady in time window whose size is $n_{wd}\Delta t$ (nwd is the number of the window's time points, Δt is the interval of time series' time points), thus we could use the method of moment or least-squares procedure etc. to estimate ARMA parameters of this segment. Therefore by moving window continuously, we could gain time vary ARMA model's parameter functions Φp(t)、θq(t).

3. CHECK OF TIME VARY ARMA MODEL

After fixing three functions: Φp(t), θq(t) and σe(t), time vary ARMA seismic model is also fixed. According to (1), time vary ARMA (2,1) and ARMA(4,2) seismic models are expressed as (7) and (8) respectively:

$$W(t) = \phi_1(t)W(t-1) + \phi_2(t)W(t-2) + \sigma_e(t)\alpha_k(t) - \theta_1(t)\sigma_e(t-1)\alpha(t-1) \tag{7}$$

$$W(t) = \phi_1(t)W(t-1) + \phi_2(t)W(t-2) + \phi_3(t)W(t-3) + \phi_4(t)W(t-4) + \sigma_e(t)\alpha_k(t) - \theta_1(t)\sigma_e(t-1)\alpha(t-1) - \theta_2(t)\sigma_e(t-2)\alpha(t-2) \tag{8}$$

The parameters have the same meaning in the formula above as in the formula (1).

As long as it produces different flat noise series α, then it will produce different analog wave series. To check that the time vary ARMA seismic model that has built is whether suitable or not, we judge it by way of examining fitting degree of the simulated seismic wave that the model has generated and target wave. Fitting degree could be determined through the residual error between analog wave and target wave is whether flat noise or not. Moreover we draw power spectral density map and response spectrum map of analog wave and target wave, from qualitative angle analysis of the difference of frequency spectrum between analog wave and target wave which are simulated, and from another angle verifyication of the rationality of time vary ARMA seismic wave model that we presented.

The residual error between analog wave and target wave could be expressed as (9):

$$\varepsilon(t) = \frac{1}{\sigma(t)}[(-\sum_{j=1}^{q}\theta_j(t)\sigma(t-j)\varepsilon(t-j) + \sum_{j=1}^{p}\phi_j(t)W(t-j+1)] \tag{9}$$

The examination of residual flat noise can change into the issue that Qk is whether or not the distribution of central χ2 whose degree of freedom is K, namely χ2 examination method, Qk is defined as (10):

$$Q_K = \sum_{k=1}^{K}[\sqrt{n}\hat{\rho}_k(n,\varepsilon_k)]^2 = n\sum_{k=1}^{K}\hat{\rho}_k^2(n,\varepsilon_k) \tag{10}$$

In the formula:

$$\hat{\rho}_k(n,\varepsilon_k) = \frac{\hat{\gamma}_k(n,\varepsilon_k)}{\hat{\gamma}_0(n,\varepsilon_k)}, \qquad \hat{\gamma}_k(n,\varepsilon_k) = \frac{1}{n}\sum_{j=1}^{n-k}\varepsilon_j\varepsilon_{j+k} \tag{11}$$

We calculated Qk, and then could look up corresponding $\chi^2_{K,\alpha}$ from the statistic chart according to a and K. If $Q_K^2 \le \chi^2_{K,\alpha}$, then we affirm original assumption, namely the model and the series investigated matching well; if $Q_K^2 > \chi^2_{K,\alpha}$,then we negate the assumption.

4. THE EXAMPLE ANALYSIS

WINSIM is simulated seismic wave's generating program that is which the author makes use of Visual C++ and CNL to develop and that is based on time vary ARMA seismic model. The following passage, we will explain time vary ARMA seismic wave model's construction and testing process that is put forward by this text through examples. For the sake of explaining it easily, time vary ARMA (4,2) model and time vary (2,1) model that are built by ambulation window method are shortened TVARMA(4,2) model and TVARMA(2,1) model, while the ARMA method that adopts intensity modulation method is shortened ARMA (2,1) model.

4.1 Constructing the model

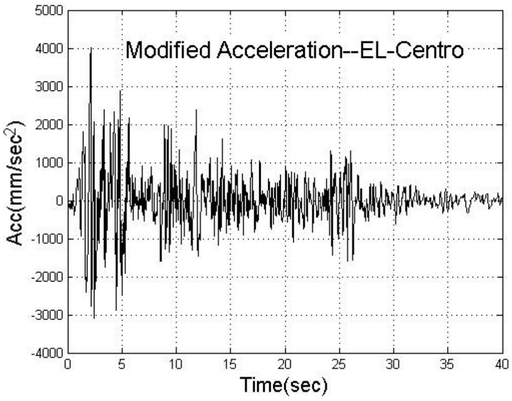

Figure 1 target wave

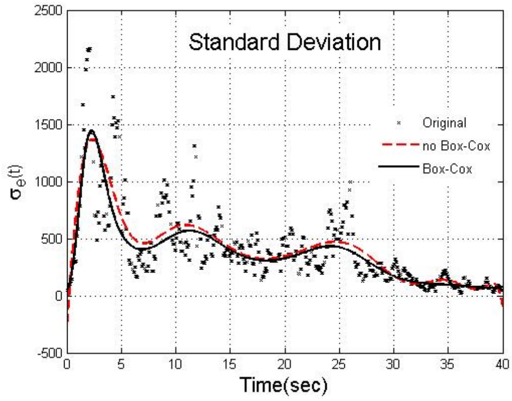

Figure 2 standard deviation function

The example selects El-Centro acceleration wave as sample wave, the interval is 0.02 seconds. According the method of section 2.1, modifying the sample wave, we get target wave, such as figure 1.

In figure 2, the imaginary line is standard deviation function map that is not solved by Box-Cox transform, in starting point and ending point of the curve, there is sharp knee phenomenon and negative standard deviation phenomenon appears which obviously doesn't matching with practice. That appears just because of adopting high order polynomial fitting. Through Box-Cox transform, we could relieve effectively the disadvantage, such as the real line of figure 2, among them, the value of λ is critical. For different wave, it has different value, in this sample, λ is 0.

While using time-moving window method to estimate the ARMA parameter, deciding the size of the window is selected according to trial method. Take TRAMRMA (2,1) model speaking, it is suitable that the size of the window is generally 3~5 seconds. Take El-Centro wave speaking, its corresponding time vary ARMA (2,1) model' parameter function is as figure 3 shows, and the size of the window is 5 seconds; take Northridge wave speaking, its corresponding TRARMA(2,1) model' parameter function is as figure 4 shows, and the size of the window is 5 seconds.

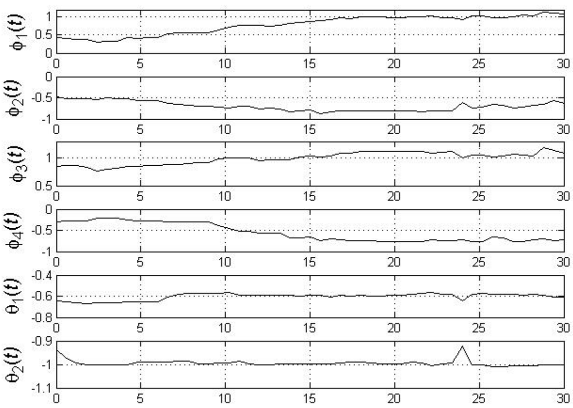

Figure 3 TVARMA(4,2) parameter diagram

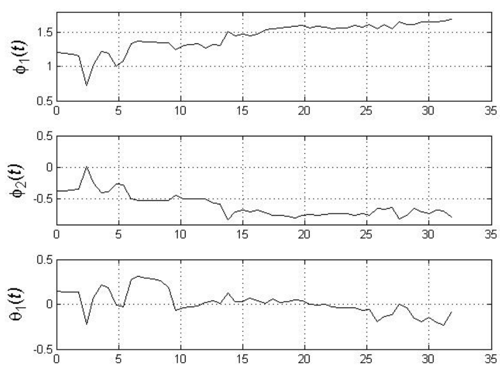

Figure 4 TVARMAs(2,1) parameter diagram

But for TVARMA(4,2) model, according to the trial result, the width of the window wants 7.5 seconds, otherwise the phenomenon of non-convergence will appear.

4.2 The check of the model

Choose TVARMA(4,2) and TVARMA(2,1) model to generate analog wave, whose appearance is basically similar, as figure 5 shows. While choose ARMA (2,1) model to generate analog wave, whose amplitude is smaller, as figure 6 shows.

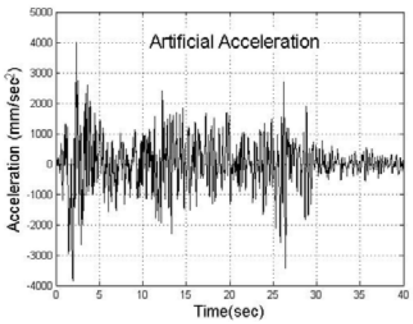

Figure 5 analog wave (TVARMA(4,2) model)

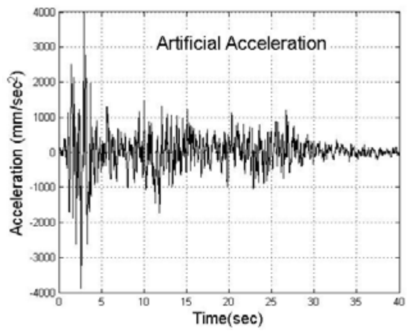

Figure 6 analog wave(ARMA(2,1) model)

4.2.1 Related analysis of the model category

From auto-correlation function (figure 7) and partial correlation function (figure 8) of target wave, we could see that there is obvious trailing smear, so we can use ARMA model to build up a seismic wave model.

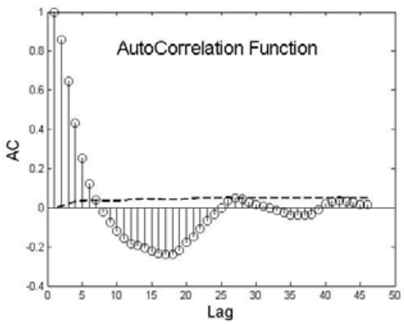

Figure 7 sample auto-correlation function diagram

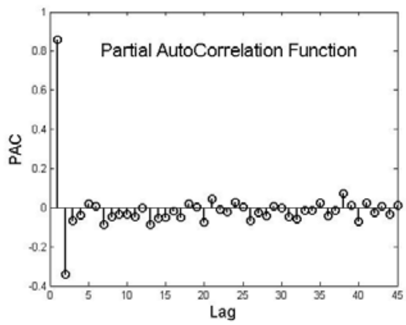

Figure 8 sample partial correlation function diagram

4.2.2 $\chi 2$ check of residual error

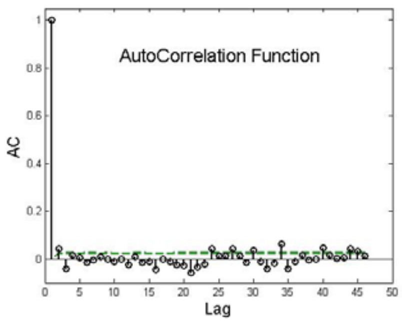

Figure 9 auto-correlation function of analog wave (TVARMA(4,2) model)

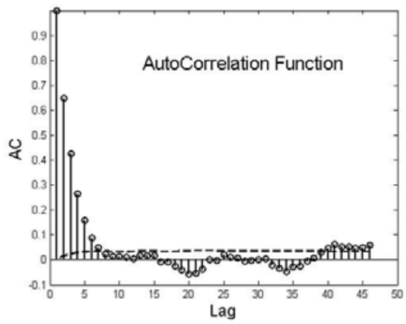

Figure 10 auto-correlation function of analog wave (ARMA(2,1) model)

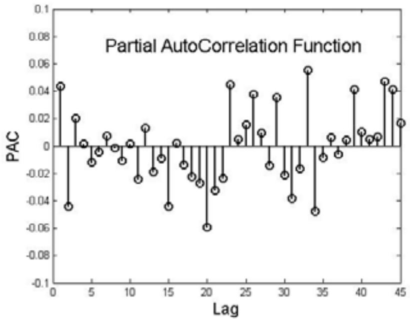

Figure 11 the partial correlation function TV of analog wave(ARMA(4,2) model)

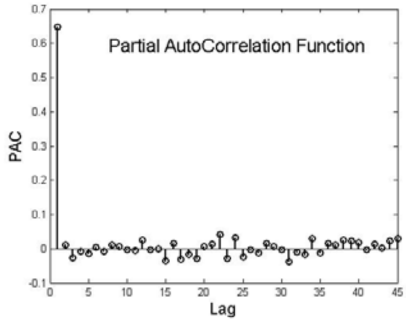

Figure 12 the partial correlation function TV of analog wave (ARMA(2,1) model)

Figure.9 and figure.10 separately describe residual error self-correlation function about TVARMA (4, 2) mode and ARMA (2, 1) mode. According to the picture of the residual error self-correlation function, we could find that the residual error ε(t) results from TVARMA mode's analogue wave has limit relationship with its initial value, however, the residual error ε(t) results from ARMA mode's analogue wave has great relationship with its initial value.

Chart.1 χ2 checking result

Target wave	El-Centro					
Model	TVARMA(4,2)	TVARMA(2,1)	TVARMA(2,1)*	ARMA(2,1)	分段 ARMA(2,1)	分段 ARMA(4,2)
Freedom	45	45	45	45	45	45
Level	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
$\chi^2_{k,a}$	73.166	73.166	73.166	73.166	73.166	73.166
Q_k	30.849	29.221	55.505	1486.29	32.874	53.742
P-value	0.193	0.0844	0.935	1.000	0.187	0.953
Conclusion	good	good	bad	bad	bad	bad

Chart.1 illustrates χ2 test results from there methods in common used, among these, there lines ahead is generated by the time-variation mode (the data with asterisk is a result which doesn't use Box-Cox transform), the forth line is a result that use the method called intensity modulation, and the fifth and sixth lines are results use the method called improvement mode according to sectionalized mode. As the P-value, it's good for us to use the time-variation ARMA (2, 1) mode we recommended and that mode has perfect effect.

4.2.3 Power spectral density comparing

The picture about the power spectral density shows average power of some frequency ωj, and it can reflect a character that the processing average power is changed with the distribution of frequencies. Figure.13 is a compared picture of analogue wave's power spectral density generated by Target wave, TVARMA (4, 2), TVARMA (2, 1) and ARMA (2, 1) mode.

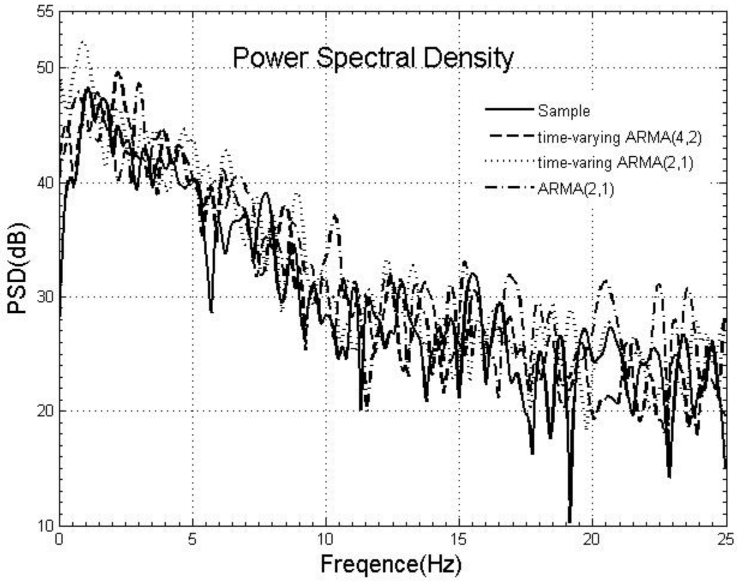

figure 13 the comparison between target waves and the analog waves-El-Centro

4.2.4 acceleration response spectrum comparison

Figure 14 is the acceleration response comparison between object wave and analog wave using different method. Among them, TVARMA(4,2) and TVARMA(2,1) used the model recommended this article, while ARMA(2,1) used strength-modulation model, SARMA(2,1) used segmentation model, TVARMA(2,1)* used time vary ARMA model without Box-Cox transformation. When the period is within one second, various models have the similar trend with the object wave. But for long period, the analog wave using TVARMA(4,2) model fitted perfectly with object model, while other analog wave regenerates wider data. The comparison of object wave、TVARMA(4,2) and TVARMA(2,1)* in long period can be obviously observed in figure 15.

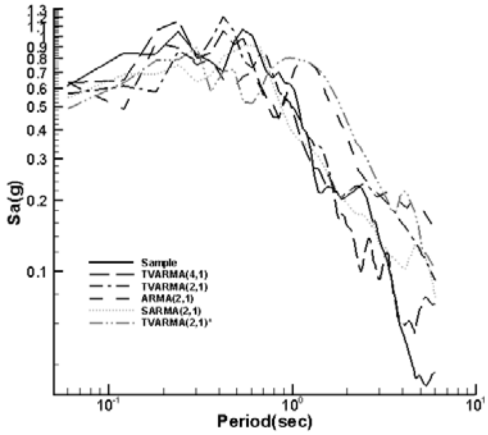

figure 14 acceleration response spectrum (unit: g，ξ=0.05)

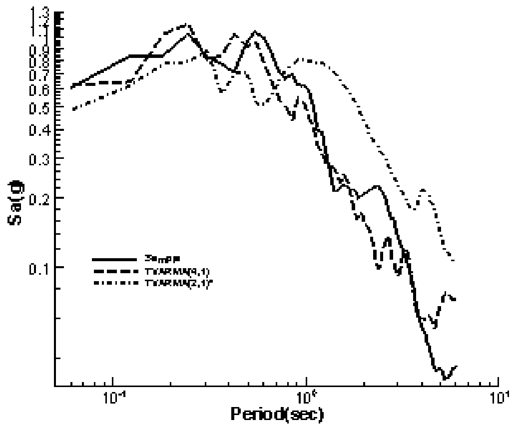

figure 15 acceleration response spectrum (unit: g，ξ=0.05)

4.3 Conclusion

The following conclusion can be made by analysis of the above illustration:

First, in the calculation of standard deviation function, polynomial fitting can smooth standard deviation function calculated by moving weighted average method, set the pace for effective peak of object wave, filter high frequency noise. In order to reduce the error produced by non-normal error and non-constant standard deviation in the sample, Box-Cox transform is used for fitted standard deviation function. The phenomenon that standard deviation function is negative due to polynomial fitting can be avoided by choosing parameter properly.

Secondly, in the cause of calculating, the parameter estimation of the time vary ARMA (p,q) model is very important. The size of the window has great influence on time-moving window method. If the window is too large, the analog parameter can't reflect non-equilibrium behavior of the system, and can't reflect rapid change of system frequency. In the contrary, if the window is too small, the calculation parameter may be unstable, and even the iteration method can't converge. Theoretically, ARMA (4,2) is better than ARMA(2,1) in the ability to reflect rapid change of system frequency. But it is found by calculation that the ability can be reflected only when the higher sampling frequency is used, such as 100 HZ.

Thirdly, the coverage range of the time-moving window is critical. If the coverage range is the same as the size of the window, then the calculation will become segment algorithm; if the coverage range is too small, operation time is too long without better accuracy; if the coverage range is too large, the relativity among various windows diminish, and the continuity of the parameter curve will be too bad. So the proper selection of coverage range can't only guarantee the continuity, but also reduce operation time with enough accuracy.

Fourthly, according to $\chi 2$ checking result (chart 1), the result of TVARMA(2,1) model is best. While the result of intensity modulation model is the worst, it is just unstable model of amplitude value, not unstable model of frequency because of that parameter calculation is used only once. As a result, that produces the bigger error. But TVARMA(4,2) model is worse than TVARMA(2,1) model, for TVARMA(4,2) model need higher sampling frequency. So time vary ARMA(2,1) model is recommended for the analog of object wave.

Sixthly, from the comparison of power spectral density diagram, we can find that, on the whole period diagram, frequency intensity distribution and trend of simulated seismic wave and target wave are almost the same. Low frequency is their chief part, while their high frequency's intensity is weak. From this, we can consider that the

target wave and the analog wave simulated by way of the time vary ARMA model are consistent in frequency spectrum's characteristic.
Seventhly, from comparison of acceleration response spectrum diagrams, we can find the whole distribution is the same, some models may cause the phenomenon that the part of the period over 1 second is too large, but using the TVARMA(4,2) model will have best result.

5. CONCLUSION

Totally speaking, using real seismic wave as target wave can make the analog wave simulated even match the true characteristic of the seismic wave, but using the normal modulated target wave can make the analog wave generated relatively satisfy the request of designing, even suit the engineer's usage better. Seismic wave is strong non-equilibrium process, and is non-normal, while in the past the majority models directly carry on calculation without handling in calculating standard deviation function, which is not reasonable. So the text brings the Box-Cox transform into the Stochastic Seismic Model, which solves the problem perfectly, and the model can realize that amplitude value and frequency are double non-equilibrium. By means of residual error$\chi 2$ checking for the analog wave generated and the target wave, the result proves that the effect of the model is better than other relative models; besides, frequency spectrum analysis also shows that the frequency spectrum characteristics of the analog wave and target wave are consistent, thereby which proves recommended model can simulate real seismic wave effectively.
Certainly, the method in this text still has many shortages and problems, the key of this model is the selection of the suitable sample wave, which requests that ground condition where the wave occurs and building ground condition must be consistent. Other problems are such as changing the shape of time-moving window, considering further the relation between model parameter and geology parameter, and that the influence to the choice of time vary parameter by the differences of analog seismic wave's response in architecture earthquake need solved and perfected further.

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