Investigation of Shaking Characteristics of ET Excitation Functions Using Effective Number of Cycles of Motion

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SUMMARY:

Endurance Time (ET) method is a dynamic analysis procedure using intensifying accelograms which are generated so that structural performance could be assessed at different excitation levels. The ET accelograms which have been generated so far have only the response spectra consistency- i.e. the duration consistency has not been directly considered. Shaking characteristics used in this study is the effective number of cycles. There are so many approaches for cycle counting. All of these approaches are applied to ET records and these parameters are evaluated in various hazard levels. Target time for each cycle counting definitions and different series of ET accelerograms are calculated. Also, some equations are proposed for predicting the number of cycles for ET records at different times of motions. Finally, a new approach is proposed for determining target time considering the number of cycles of motions. The results highlight the necessity of considering the duration consistency for ET records.

Keywords: *Effective number of cycles, Endurance time method, intensifying accelerograms, dynamic analysis.*

1. INTRODUCTION

For characterizing a motion; amplitude, frequency content and strong motion duration of that motion should be investigated. Linear acceleration spectrum can be used to consider the influence of the amplitude and the frequency content of a motion. It refers that whenever only linear acceleration spectrum is employed for characterizing a motion, implicitly the influence of the duration of that motion in response of structures, is neglected. This effect would be negligible if under earthquake motion the structure remains elastic; however this premise is strongly wrong when the structures exhibit nonlinear behavior [Hancock and Bommer, 2006., Bommer and Martinez-Pereira 1999]. As a result, in nonlinear dynamic analysis the influence of strong motion duration should be considered.

Recently, performance-based design is becoming more popular among engineers. In this method, to evaluate the performance of a structure, seismic demand of that structure should be determined using either nonlinear static procedure-hereafter NSP; or nonlinear dynamic procedure-hereafter NDP. It is obvious that nonlinear characteristic of material and geometry should be considered in structural model. Nonlinear response of structures using NDP is predicted in more accursedly way than NSP. There are some obstacles in NDP such as the dispersion of the results. These obstacles and the simplicity of NSP motivate engineers to employ NSP as a method for determining the seismic demand of structures. Endurance time analysis, hereafter ET analysis, is a dynamic analysis in which some of deficiencies of conventional NDP are removed, and it is simpler than NDP as well. The main difference between ET analysis and NDP is their input motion. The predesigned intensifying accelerograms, hereafter ET accelerograms, is used as input motion in ET analysis against the real recorded motion which is used in NDP. Response parameter of structures subjected to ET accelerograms is increasing during the analysis constantly. Based on the response of structure in ET analysis, performance of structure could be evaluated in different hazard levels. As a matter of fact, this feature of ET analysis which performance of a structure at different hazard levels can be determined by one time history analysis, make this method more practical to use in performance based design. As much as the ET accelerograms would be more reflective of the real ground motions, the result of ET analysis would be more reliable. The compatibility of linear and nonlinear spectrum of the real ground motion and the ET accelerograms has been considered in the generation process of current ET accelerograms, however, the duration consistency of them has not been considered directly. Some authors suggest that effective number of cycles can reflect the influence of strong motion duration in itself. In this paper, the effective number of cycles associated with ET accelerograms and real ground motion is compared and afterwards, procedure is suggested to make better duration consistency between ET accelerograms and real ground motions.

2. REFERENCE GROUND MOTION SET

This study utilizes the far-field record set for non-linear dynamic analysis which is proposed by FEMAp695 code. These records are considered to be applicable to structures located at different sites with different ground motion hazard functions, site and source conditions.

3. MAKING UP OF ET ACCELEROGRAMS

In ET analysis, structures are subjected to predesigned intensifying excitation functions and performance of those structures are evaluated at different hazard levels based on their response at times corresponding to those hazard levels. For example, if target time of an ET accelerogram is 10sec, target time is the time in which an ET accelerograms produces target spectrum, responses of structures at 10sec could be used to evaluate the performance of structures in DBE hazard level. Acceleration spectrum of an ET accelerogram is increasing through time constantly. Based on acceleration spectrum produced by ET accelerogram at a time window, that time window can be assigned to special hazard level. Fig. 3.1 and Fig. 3.2 are an example of the mentioned assignation of hazard levels:

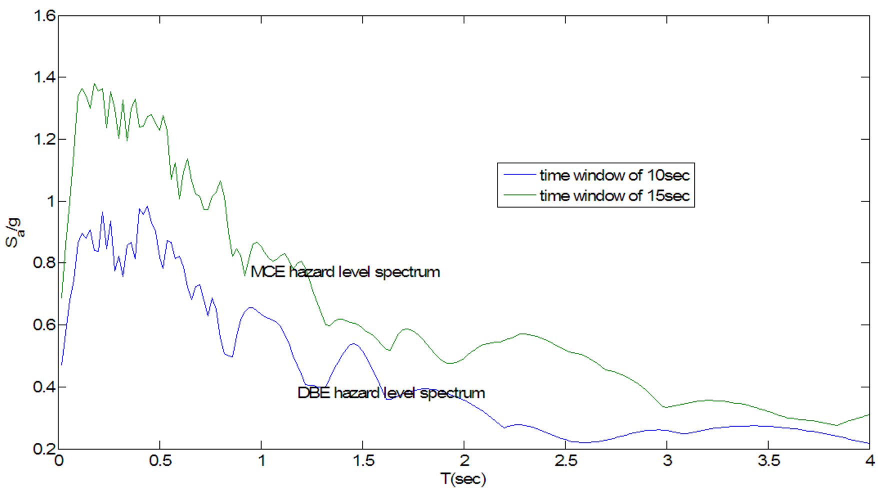

Figure 3.1. Determination of hazard level of the ETA20a01accelerogram

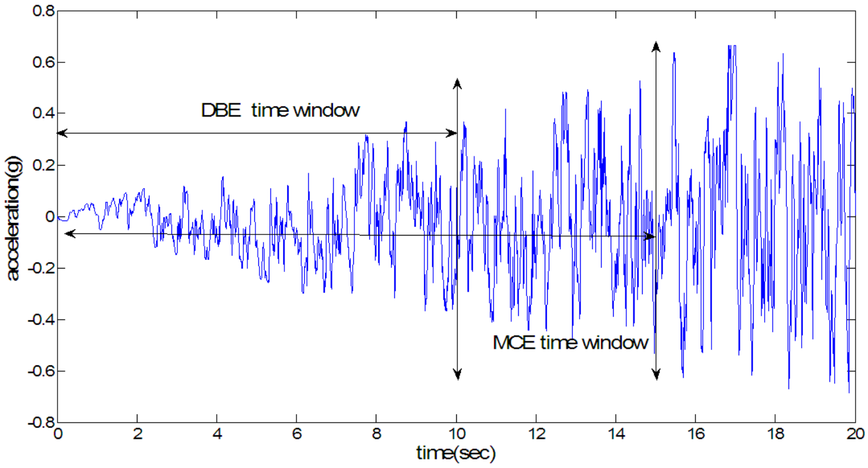

Figure 3.2. Assignation of hazard level to time window

Recently, broad research has been trying to generate ET accelerograms which would be more accurate than current ones. In the second generation of the ET excitation functions, the concept of response spectrum and numerical optimization were introduced and numerically significant results were achieved [Valamanesh and Estekanchi, 2010]. By extending the range of period of vibration into very long periods, records in this generation produced highly reasonable estimates in non-linear range of behavior as well [Riahi and Estekanchi, 2010]. In the third generation, non-linear response spectra were included in the optimization procedure [Estekanchi et al.2009. Nozari and Estekanchi, 2011]. This study uses four series of ET accelerograms which are presented in Table 1.

Table 3.1. Characteristics of studied ET accelerograms in this article

Series	Target spectrum	Long periods included	Non-linear optimization
ETA20a	code spectrum (standard 2800)*	N	N
ETA20e	average of several recorded motion on stiff soil	Y	N
ETA40g	code spectrum (ASCE standard)	Y	N
ETA20en	average of several recorded motion on stiff soil	-	Y

*Iranian national code

4. REVIEW OF CYCLE COUNTING DEFINITIONS

There are many different cycle-counting definitions used in earthquake engineering field, but all cycle-counting approaches can be divided into five generic groups, as following [8]:

- Peak counting
- Level crossing counting
- Range counting
- Indirect estimation
- Definitions based on structural response.

One group of these definitions counts cycle ranges (from peak to trough), whereas others count cycle amplitudes (from the zero baseline to the peak). The first one is classified as range-counting.
A cycle counting definition is classified as peak counting if it counts the number of peaks in the strong-motion [Hancock and Bommer, 2005]. And one of these definitions only counts the largest peaks between zero crossings, whereas others count all peaks.

Range-counting are usually used for assessment of fatigue damage [Hancock and Bommer, 2005]. The most popular range-counting method is the rain-flow counting. It counts both high-and-low frequency cycles in broad-banded signals [Hancock and Bommer, 2005].

Malhotra [Malhotra, 2002] used the method of half-cycles to accumulate damage caused by individual cycles. The damage expression can be re-written as Eqn. 4.1:

$$D = C \sum_{i=1}^{2tn} u_i{}^c \qquad (4.1)$$

Where, u_i is the amplitude of i-th half-cycle, u_{max} is the largest amplitude of half cycles, and tn is the total number of cycles. C and c are application-dependent damage coefficients: c is a linear scale factor and c determines the relative importance of different amplitude cycles.
Moreover, Malhotra [Malhotra, 2002] divided the cumulative damage D by damage caused by the largest full-cycle amplitude, u_{max},to obtain the equivalent number of cycles (of amplitude u_{max}) which causes the same damage to a structure compared to the entire deformation history, i.e.

$$N_{cy} = \frac{1}{2} \sum_{i=1}^{2tn} \left(\frac{u_i}{u_{max}}\right)^2 \qquad (4.2)$$

values of c=2, C=1 are adopted for this study.
A significant criterion for differentiating among various definitions is if they are calculated using the absolute amplitude of the cycles or employing levels relative to the cycle with largest amplitude (u_{max}). Damage parameter given in Eqn. 4.1 is typical of an absolute measure; moreover, the definition of the effective number of cycles given in Eqn. 4.2 is typical of relative measure of the number of cycles in the motion [Hancock and Bommer, 2005].

In this study, peak counting uses zero crossing, peak counting uses non-zero crossing, and rainflow counting which is completely described by ASTM [ASTM, 1985], are employed. In all cases, damage parameter given in Eqn. 4.1and the effective number of cycles given in Eqn. 4.2, are applied to quantify the number of cycles in a motion which has cycles with different amplitudes.

5. INTRODUCTION OF NUMBER OF CYCLES SPECTRUM

The number of cycles, which a structure should resist, is essentially different from the number of cycles of input motion and significantly depends on the period of structure. Fig. 5.1. show that the effective number of cycles which structures with different periods should resist is significantly different. Effective number of cycle spectrum is a plot which draws the effective number of cycles of acceleration response of SDOF systems which are subjected to a motion, versus their period.

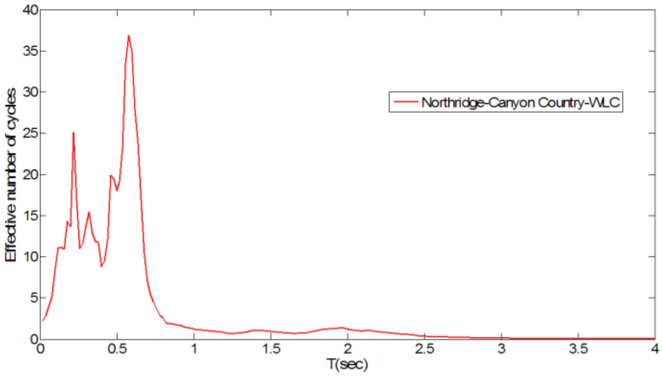

Figure 5.1. The effective number of cycles spectrum using rain-flow counting and absolute measure

The effective numbers of cycles spectrum for the real ground motions are computed. It should be mentioned that the real ground motion individually scaled at each period to the design spectrum of Iranian national building code (INBC). This implies that this spectrum does not belong to one motion, rather at each period that motion has been scaled. Fig. 5.2. shows the effective number of cycles spectrum for the real ground motions. Dispersion of these spectra is noticeable.

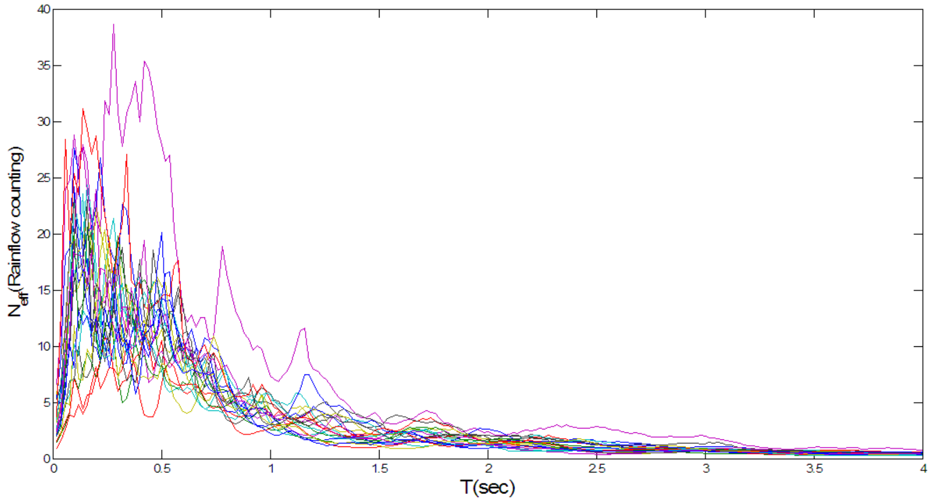

Figure 5.2. Effective number of cycles spectrum for real ground motions

6. INVESTIGATION OF THE VARIATION OF EFFECTIVE NUMBER OF CYCLES OF ET ACCELEROGRAMS THROUGH TIME

In order to quantify the effective number of cycles spectrum, area under this curve is considered as a parameter conveying the information of number of cycles in different periods [Mashayekhi and Estekanchi, 2012]. This parameter is referred hereafter as $N_{c-spectrum}$. This parameter is calculated for different excitation level to realize how $N_{c-spectrum}$ is changed through time. Fig. 6.1. exhibits that this parameter changes as a quadratic function of time for ETA20a series of ET accelerograms.

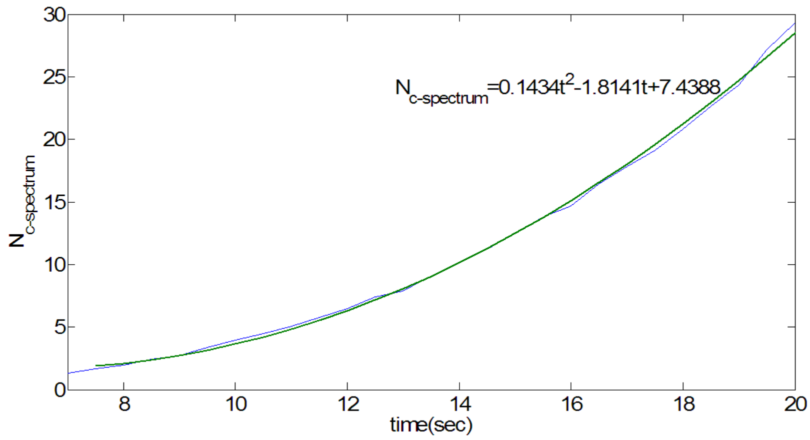

Figure 6.1. Variation of number of cycles through time for ETA20a series of ET accelerograms

If at any excitation level, the ET accelerograms have scaled so that they produce the target spectrum, Fig. 6.2. shows that the variation of $N_{c-spectrum}$ is linear against the quadratic variation of $N_{c-spectrum}$ when scaling process have been done only at target time.

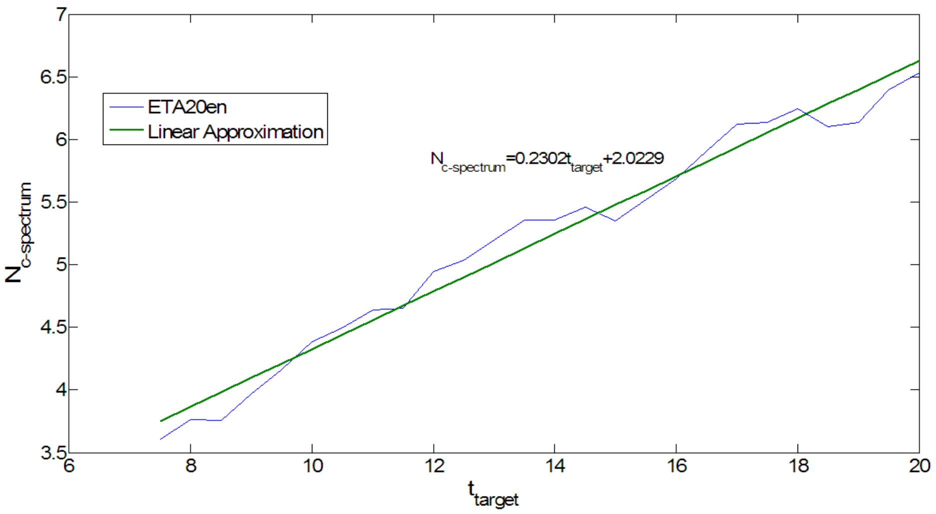

Figure 6.2. Variation of number of cycles against the target time

7. COMPARISON OF NUMBER OF CYCLES OF REAL GROUND MOTIONS AND ET ACCELEROGRAMS

This section consists of two parts. First one is for investigating the target time and second one is for investigating the MCE time of ET accelerograms.

7.1. Determination of Target Time in ET Accelerograms

In this section the target time is determined so that the $N_{c-spectrum}$ of the real ground motions and ET accelerograms are consistent. Fig. 7.1. shows an example of this procedure for ETA20a series.

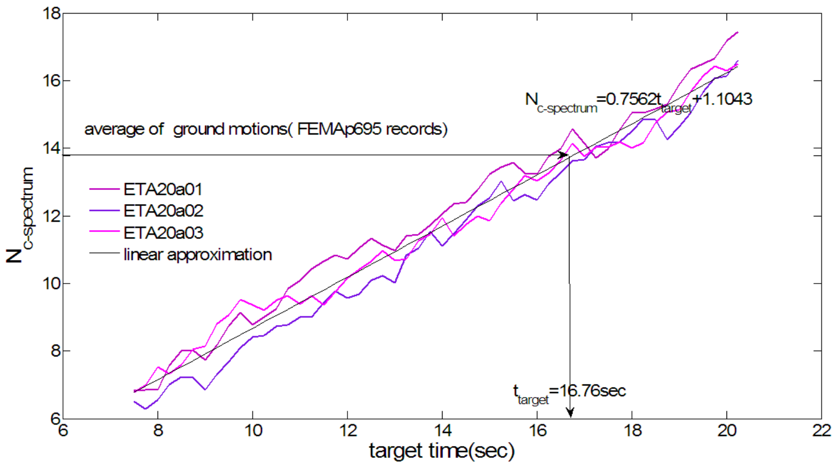

Figure 7.1. Determination of target time to make best duration consistency for ETA20a

Table 7.1. represents the target times which guaranty the duration consistency between ET accelerograms and real ground motions.

Table 7.1. Proposed target time for different cycle counting method and different series of ET accelerograms

	Target time (sec)		
Series	**Zero crossing (abs*)**	**Non zero crossing (abs)**	**Rain-flow counting (abs)**
ETA20a	14.77	14.76	16.76
ETA20e	13.55	13.37	14.79
ETA40g	15.63	15.80	17.45
ETA20en	14.48	14.41	15.94

Table 7.1. shows that target time about 10sec seems to be appropriate for all different series of ET accelerograms and different cycle counting definitions. It means that if ET accelerograms produce the target spectrum at 15sec, the number of cycles which structures, subjected to ET accelerograms, should resist is consistent with those structures should resist when they are subjected to the real ground motions.

7.2. Determination of MCE Time in ET Accelerograms

In this section, time in which $N_{c-spectrum}$ of ET accelerograms and real ground motions are consistent is determined. For this purpose, target time is fixed at 15 sec, afterwards $N_{c-spectrum}$ is plotted against time and MCE time is determined. This procedure is depicted in Fig. 7.2. as well:

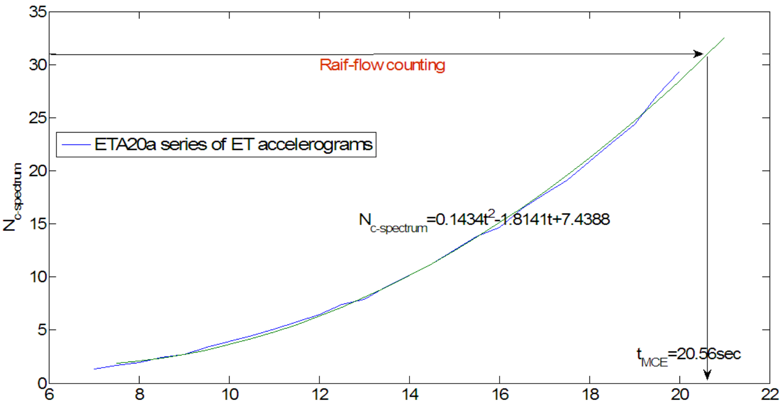

Figure 7.2. Determination of MCE time for ETA20a

Results of MCE time for different series of ET accelerogram and different cycle counting is presented in table 7.2.

Table 7.2. MCE time for different series of ET accelerogram and different cycle counting

	MCE time(sec)		
Series	**Zero crossing (abs)**	**Non zero crossing (abs)**	**Rainflow counting (abs)**
ETA20a	19.67	19.73	20.56
ETA20e	19.52	19.45	20.19
ETA40g	20.79	20.85	21.39
ETA20en	19.85	19.82	20.44

Table 7.2. shows that MCE time about 20sec approximately is suitable for different series of ET accelerograms and different cycle counting method.

8. INVESTIGATION OF PROPOSED TARGET TIME IN MATCHING THE EFFECTIVE NUMBER OF CYCLES

Fig. 8.1. shows the effective number of cycles spectrum of real ground motions to be compared with ET accelerograms at target time equal to 10 sec and target time which is proposed in pervious section.

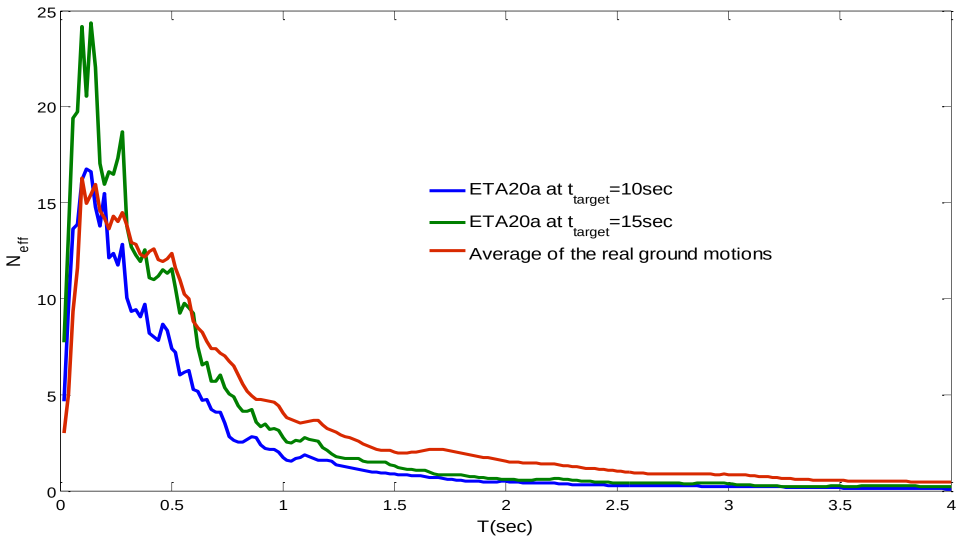

Figure 8.1. Comparison of the effective number of cycles spectrum of real ground motion and ET accelerograms

It is obvious that the proposed target time only guaranties the equality of area under effective number of cycles spectrum. At proposed target time, effective numbers of cycles at high periods are smaller than those associated with real ground motions and at low periods this trend is distinctly reverse. For the sake of quantification, δ parameter is defined as Eqn. 8.1.

$$\delta = \sqrt{\sum \frac{1}{N} \left(\frac{SN_{ac} - SN_{aET}}{SN_{ac}} \right)^2} \tag{8.1}$$

Where SN_{ac} is the effective number of cycles associated with real ground motions at period T, SN_{aET} is the effective number of cycles of ET accelerograms and N is total number of periods is used to calculate δ parameter. To investigate the situation of the effective number of cycles of ET accelerograms compared to the real ground motions, two general intervals for periods is chosen. First [0.02-0.5] as representative of low period interval and [0.5-4sec] as representative of high period interval. Variation of, δ parameter against the target time is plotted in Fig. 8.2. and Fig. 8.3.

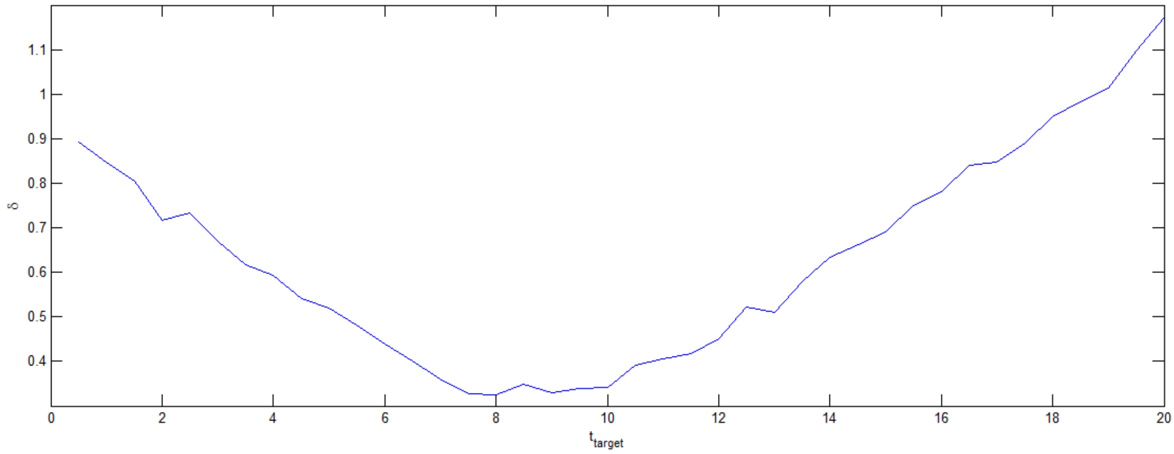

Figure 8.2. Variation of δ parameter against target time for interval of [0.02-0.5]

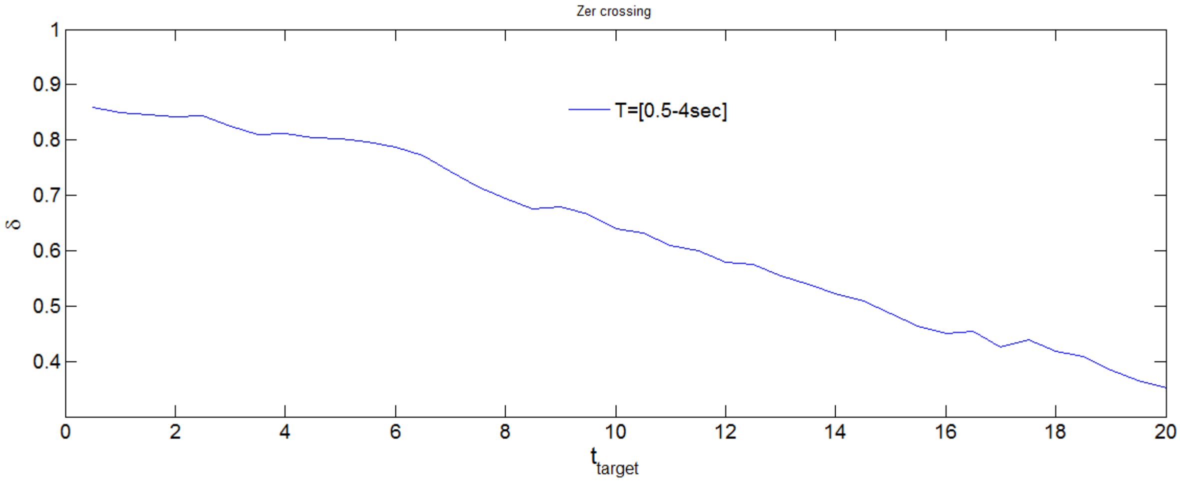

Figure 8.3. Variation of δ parameter against target time for interval of [0.5-4]

Fig. 8.1. and Fig. 8.2. emphasize that for low periods target time should be shifted to time about [8-10] second but for long periods target time should be shifted to time about [18-20] second. generally target time about 15 second satisfies duration consistency almost for all periods.

9. CONCLUSION

In this paper some different definitions for cycle counting of a motion are reviewed. Also, one approach, which considers the response of SDOF systems rather than input motion, is recommended. This approach named number of cycles spectrum that is suitable for all structures with wide range of periods, on the other hand using the input motion that is only suitable for structures with low periods. Besides, for quantification of the effective number of cycle spectrum, $N_{c-spectrum}$ is defined as area under the spectrum.

Moreover, in this paper the concept of ET analysis is reviewed; and proposed approach for cycle counting is imposed to ET accelerograms. Comparison between the $N_{c-spectrum}$ of the real ground motions and ET accelerograms shows that target time about 15 second is suitable for making the duration consistency between ET accelerogram and real ground motions. This proposed target time is examined to illustrate how much consistency is guaranteed with this target time. The results show that this target time necessity cannot guaranties the best duration consistency. For low periods, for best duration consistency target time should be shifted to time before 10second and for long periods, target time should be shifted to time after 18 second. It is not possible to determine distinct target time for each individual structure, so it seems reasonable to approve 15 second as target time. To sum up, for exact matching between number of cycles of the ET accelerograms and the real ground motions, the equation of number of cycles should be included in generation process of ET accelerograms.

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