A New Procedure for Selection and Modification of Strong Ground Motion for Nonlinear Dynamic Analysis

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SUMMARY:

Nonlinear dynamic analysis is known as the most accurate method to evaluate the behavior of structures during an earthquake. In this context, the selection process of suitable records and their modification plays a vital role. An effective selection and modification of ground motion as the loads to be used in the analysis can lead to responses with low dispersion in nonlinear structural analysis. This in turn, results in much more trust in the safety of the designed structure. This fact highlights the importance of the current study.
Screening process is a three-stage operation as the Coarse, Medium, and Fine-Screen sub-processes. The remaining records are modified in order to minimize the scatter in the results of nonlinear dynamic analysis of the structure under study, by calculating scale factors by different methods to be multiplied to the selected earthquake time histories. The proposed method results in least scatter in representative nonlinear dynamic response quantities.

Keywords: ground motion selection and modification, nonlinear dynamic analysis, scatter

1. SELECTION OF GROUND MOTION FOR SEISMIC DESIGNING

The evaluating seismic characteristic of the structures and studying their behavior under applying the pressure of loads resulting from earthquake by using nonlinear dynamic analysis, it requires using a type of loading, because this loading is critically studied for a structure. Regarding to the fact that earth earthquake loading is entirely accidental, it should have some properties which are optimized for mentioned structure and can apply sufficient energy on structure. Therefore, the records should be selected based on seismic properties of area for analyzing nonlinear time history that:

- Seismic characteristics of them are equal to studied area.
- Can provide most critical seismic state for the structure.
- Response resulting from structure analysis which has been done by using these records indicate lowest dispersion amount in definite parameters of response.

In this manner, selection of proper ground motion and also the method of scaling it that affects on nonlinear responses of the structures can result in different results. When a selection can be called optimization by time that all effective parameters are correctly selected and can plays a vital role. While it is considered that the number of records from present resources are extracted for a specific area or in more complicated conditions when there are no any useful information about past earthquakes for a specific area, just geological data are taken into consideration and parameters are used. Ground motion due to the earthquake and it duration in specific place are influenced by numerous factors that most important one are as follows: earthquake magnitude, the distance of source releasing energy to place, state of place soil, transformation in geological context and dispersion rate along motion route, state of earthquake resource and its mechanism. In following numerous mentioned parameters are explained upon selecting the records.

1.2. Selection of Record Based on Magnitude and Distance

One of the most important parameters which is used on evaluating nonlinear dynamic is parameter earthquake magnitude. Because earthquake magnitude can express released energy limitation while occurring an earthquake and since released energy has a direct relation with shaking range resulting from earthquake center, it can be an effective factor on selecting ground motion of the regions where have no seismic data.

One of other basic parameters that play a role to select ground motion by magnitude is parameter of distance, because the distance from a source of releasing energy leads to transform ground motion. For example, it affects directly on earth peak acceleration. The distance from a source of releasing energy affects on peak speed changes, so that reducing the speed is relatively faster than reducing acceleration and contrary to reduce velocity, speed reduction is depending on soil condition.

1.3. Assisting Principles for Selecting Ground Motion

As it is mentioned, other parameters can effect on selecting ground motion, therefore, geology of the region is one of those parameters. Soil condition affects on ground motion and its reduction, thus selection of ground motion cannot be done without considering this main parameter. The researcher believe that soil condition has a great effect on speeds and displacement, but horizontal acceleration is not influenced by soil condition amount its amount is equal for the stone and the soil, though soil condition can particularly, soft soil can affect on peak velocities.

1.4. Process of Screening for Selecting Ground Motion

As it is expressed, one of guidelines that can directly affect on reducing responses' dispersion, optimal selection of ground motion are used as seismic loading in analysis. In this context, a three stage process is proposed for selecting ground motions that's entitles "screening process". This set of screening is in this form that begins from coarse screening and accordingly leads to smaller classification, namely finer screenings and results in exiting at every stage of selected motion and other groups of trend. Therefore, three classifications including coarse, medium and fine screening are defined. In following it is expressed to study this trend of screening.

1.4.1. Coarse screening

In coarse screening, following ground motion parameters are explained: magnitude and regional characteristic parameters, i.e. distance to caused fault, type of local soil and fault for selecting the records from international reference of ground motion, pacific earthquake engineering center (peer Berkeley) is used. According to ASCE 7-10, it is necessary to take into consideration that selected ground motions should include the history of horizontal acceleration that is recorded from areal event and also these records should have the values of magnitude, distance to the fault and resource mechanism that comprise maximum considered earthquake. Basically, peer database are used for selecting ground motions. In this database, 7638 motions are recorded that those are contrary to proposed regulation (hypothesizes of research) have to be removed from selection circle. It performs in stage from. In the following, the effect of each parameter on selecting ground motions are studied by using those parameters and data characteristic of constructing the building:

Stage 1:

- If there is no limitation for M, R and fault mechanism.
- ✓ Number of selected records: 7638

Stage 2:

- There is limitation for M.
- There is no limitation for R, soil type and fault mechanism.
- ✓ Number of selected records: 2937

The number of selected are indicated based on different values of magnitude in following table.

Table 1. Effect of magnitude on selecting ground motion

#	Magnitude	NO,
1	5<M<5.5	253
2	5.5<M<6	602
3	6<M<6.5	2500
4	6.5<M<7	437
5	7<M<7.5	222
6	7.5<M<8	482

Stage 3:

- There is limitation for R.
- There is no limitation for M, soil type and fault mechanism.
- ✓ Number of selected records: 712

The numbers of selected records are indicated based on different values of distance.

Table 2. Distance effect on selecting ground motion

#	Distance(Km)	NO,
1	0<R≤20	375
2	20<R≤50	712

Stage 4:

- There is limitation for M, R, soil type and fault mechanism.
- ✓ Number of selected records: 41

In following table, the effect of each parameter is presented based on the number of selected records.

Table 3. Using determined parameters to select ground motion

#	Magnitude	Distance(Km)	Site Class	Strike-slip	Normal	Reverse	Reverse-oblique	Normal-oblique	No, of Total Record Selected
1	5<M<5.5	0<R≤20	No	0	0	0	1	0	1
2	5<M<5.5	0<R≤20	Site Class C	0	0	0	0	0	0
3	5<M<5.5	20<R≤50	No	0	0	0	0	1	1
4	5<M<5.5	20<R≤50	Site Class C	0	0	0	0	1	1
5	5.5<M<6	0<R≤20	No	21	2	14	53	0	90
6	5.5<M<6	0<R≤20	Site Class C	5	1	10	26	0	42
7	5.5<M<6	20<R≤50	No	6	6	79	55	0	146
8	5.5<M<6	20<R≤50	Site Class C	2	1	43	19	0	65
9	6<M<6.5	0<R≤20	No	25	5	23	8	3	64
10	6<M<6.5	0<R≤20	Site Class C	7	2	18	1	1	29
11	6<M<6.5	20<R≤50	No	24	10	259	15	0	308
12	6<M<6.5	20<R≤50	Site Class C	9	4	155	6	0	174
13	6.5<M<7	0<R≤20	No	41	7	55	21	0	124
14	6.5<M<7	0<R≤20	Site Class C	2	2	32	14	0	50
15	6.5<M<7	20<R≤50	No	15	4	81	29	0	129
16	6.5<M<7	20<R≤50	Site Class C	0	2	41	15	0	58
17	7<M<7.5	0<R≤20	No	14	0	6	0	0	20
18	7<M<7.5	0<R≤20	Site Class C	9	0	4	0	0	13
19	7<M<7.5	20<R≤50	No	16	0	4	0	0	20
20	7<M<7.5	20<R≤50	Site Class C	7	0	2	0	0	9
21	7.5<M<8	0<R≤20	No	7	0	0	71	0	78
22	7.5<M<8	0<R≤20	Site Class C	2	0	0	52	0	54
23	7.5<M<8	20<R≤50	No	6	0	1	102	0	109
24	7.5<M<8	20<R≤50	Site Class C	3	0	0	50	0	53

According to above table the numbers of 41 records are selected by coordinated proposed properties. These records have a magnitude in the range of 6.5 to 7 and distance to the fault is Between 20 to 50 Km and soil type is all of type c and regarding to fault type of the region is selected by these records.

It presents various mean amounts of magnitude and distance that can considerably affect on reducing responses' dispersion of nonlinear time history analysis.

1.4.2. Medium screening

The methods which are expressed under the title "medium screening" in this section are selected among a lot of methods of selecting ground motions which are more practicable and individual capability is confirmed each one these methods is introduced in subsequent sections and measuring the amount are performed by those methods different methods which apply under title of medium screening are as follows

1.4.2.1. Spectrum balance

The basis of this method is find coefficient of optimum scale, comparison of standard spectrum and spectrum acceleration resulting from used accelerograms. In this method, the ratio of area under diagram of spectrum of recording acceleration to all area of diagram is 1.4 times standard spectrum that is considered as a balancer of acceleration spectrum and a modification coefficient for cohort acceleration records to peak acceleration of region.

1.4.2.2. Spectrum intensity

It is a criterion of reconstruction rate of structure that has been expressed by using contribution of absorbed seismic energy via a structure while occurring the earthquake which spectrum velocity or semi speed is a function of alternate time and structure descanting. Spectrum intensity (SI) consist the area under diagram of velocity spectrum (SV). For scaling acceleration spectrum, it can be acceleration considered that spectrum intensity is measured between both specific alternate times and acceleration recorder divided up.

1.4.2.3. Mean spectrum deviation

In this method, present dispersion in record is simply determined by mean acceleration domain at determined distance of alternate times and is a criterion for selecting the records. The amount indicates distance of mean spectrum of a record that is a representative of that parameter and determines present dispersion in a record and puts it a criterion for selecting record. Whatever the amount of this measured deviation is lower, studied record corresponds further with target spectrum. One particular basis, following relation is used:

$$\delta_i = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{S\alpha_j(T_i)-S\alpha_{REF}(T_i)}{S\alpha_{REF}(T_i)}\right)^2} \tag{1}$$

In the above equation, $S\alpha_j(T_i)$ represents the pseudo-acceleration ordinate of the real spectrum j at period Ti, $S\alpha_{REF}(T_i)$ is the value of the spectral ordinate of the code spectrum at the same period, and N is the number of values used within a pre-defined range of periods. Whatever the level of calculated deviation is lower, studied record is further agreement with target spectrum.

1.4.2.4. Spectrum compatibility

This method is used by the purpose of finding lowest deviation of a target spectrum and its relation is follow. The values of obtained by using specific parameters.

$$D_{rms} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\frac{S\alpha_0(T_i)}{PGA_0} - \frac{S\alpha_s(T_i)}{PGA_s}\right)^2} \tag{2}$$

In the above equation, N is the number of periods at which the spectral shape is specified, $S\alpha_0(T_i)$ is the spectral acceleration of the record at period Ti, $S\alpha_s(T_i)$ is the target spectral acceleration at the same period value, while PGA_0 and PGAs are the peak ground acceleration of the record and the zero-period anchor point of the target spectrum, respectively. A small value of D_{rms} indicates closer matching between the shapes of the record and target spectra. Exploiting two indexes containing acceleration spectrum intensity and peak ground acceleration result in that calculated correspondent is depending on structural parameters and characteristics of ground motion.

1.4.2.5. Selection based on epsilon (ε)

Epsilon is most important parameter of predicting structure response. As it is said, $\varepsilon(T_1)$ is the number of logarithmic standard deviation that obtains by spectral acceleration in fundamental period of structure and the relation is as follow:

$$\varepsilon(T) = \frac{\ln Sa(T) - \mu_{\ln Sa}(M,R,T)}{\sigma_{\ln Sa}(T)} \quad (3)$$

Where $\mu_{\ln Sa}(M,R,T)$ and $\sigma_{\ln Sa}(T)$ are the predicted mean and standard deviation, respectively, of $\ln Sa$ at a given period, and $\ln Sa(T)$ is the log of the spectral acceleration of interest. The records which their epsilon values are close to zero have lowest difference of spectral acceleration at the fundamental period of structure. In fact, epsilon differences of spectrum domains are determined at a certain period.

1.4.2.6. Summary the results of medium screening

The records which are introduced as a result of coarse screening are evaluated in medium screening and by five different methods and specific parameters are measured in every method regarding to studied parameters and method performance is indicated for classification. Thus, final results of medium screening are five individual record sets. Analysis and evaluation are performed to determine optimal record set as a result of screening process by using five sets of fine screening.

1.4.3. Fine screening

Fine screening is last loop of screening chain to reach final records in the stage of selecting ground motion. Five record sets obtaining from medium screening are studied and finally best medium screenings and records in that set. Applied fine screenings are consisting of conditional means spectrum (CMS) and indexes of advanced intensity measure.

1.4.3.1. Selection of ground motion by using conditional means spectrum (CMS)

CMS presents a response that based on the characteristics of ground motion like spectral acceleration at a specific period and earthquake magnitude (M), caused fault distance (R), method of resource mechanism (F), condition of place soil (S). in this method at first, target spectrum that is as same as conditional mean spectrum.

The relation of measuring conditional mean spectrum is as follow:

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*)} = \mu_{\ln Sa}(M,R,T_i) + \rho(T_i, T^*)\varepsilon(T^*)\sigma_{\ln Sa}(T_i) \quad (4)$$

in which $\mu_{\ln Sa}(M,R,T_i)$ and $\sigma_{\ln Sa}(T_i)$ are the mean spectral acceleration and standard deviation, respectively, $\rho(T_i, T^*)$ is the correlation coefficient between two different periods, and $\varepsilon(T^*)$ is a deviatory standard logarithmic number calculated for the spectral acceleration value at the fundamental period of structure. For corresponding proposed records to target spectrum (conditional means spectrum), following relation which is called sum error squares are used.

$$SSE = \sum_{j=1}^{n} \left(\ln \mathrm{Sa}(\mathrm{T_j}) - \ln \mathrm{Sa_{CMS}}(\mathrm{T_j})\right)^2 \quad (5)$$

Where $\ln \mathrm{Sa}(\mathrm{T_j})$ is the log spectral acceleration of the ground motion at period$\mathrm{T_j}$, and $\ln \mathrm{Sa_{CMS}}(\mathrm{T_j})$ is the log CMS value at period $\mathrm{T_j}$ from equation 4.

1.4.3.2. Selection ground motions with advanced intensity measure

The power of ground motion is measured by using an index of intensity such as peak ground acceleration at specific period. In practical methods for evaluating probable shakings of a structure, intensity index have been used for estimating structural requests by using earthquake with different intensity. For example, intensity index $\mathrm{IM}_{1I\,\&2E}$ is considered as one of most complete advanced intensity measure of numerous parameters and the relation between the ratho of inelastic displacement to elastic one is studied by several free degrees. The relation of calculating this index is as follow:

$$\mathrm{IM}_{1I\,\&2E} = \mathrm{Sd}^{I}(\mathrm{T}_1, \xi_1, d_y) \times \sqrt{1 + \left[\frac{\mathrm{PF}_2^{[2]}\,.\mathrm{Sd}^{E}(\mathrm{T}_1, \xi_1)}{\mathrm{PF}_1^{[2]}\,.\mathrm{Sd}^{I}(\mathrm{T}_1, \xi_1, d_y)}\right]^2} \quad (6)$$

In above relation, $\mathrm{Sd}^{I}(\mathrm{T}_1, \xi_1, d_y)$ is the spectral displacement of an elastic-perfectly-plastic (EPP) oscillator with period T1, damping ratio ξ1, and yield-displacement d_y, for calculating this spectrum, it is necessary to calculate d_y by using Nonlinear Static−Pushover analysis, then the spectrums of inelastic response are drawn by using secondary software. $\mathrm{Sd}^{E}(\mathrm{T}_1, \xi_1)$ Is displacement response at the period T_1, $\mathrm{PF}_1^{[2]}$ and $\mathrm{PF}_2^{[2]}$ are the coefficient of contribution in first and second mode. According to obtained results with two methods of fine screening of records in second method, medium screening are introduced as final process of screening of records of spectrum intensity method. In fine screening , it makes clear that both methods of conditional mean spectrum and displacement spectrum intensity measure have perfectly similar results, but just a difference is observed that the method of displacement spectrum intensity measure has very high operational volume than the method of conditional mean spectrum, thus it is suggested that fine screening has been performed by using the method of conditional mean spectrum. At the end and after doing this three- stage process, final records are selected.

2. MODIFICATION (SCALING) OF GROUND MOTION

Three different modification methods are used in this research for scaling of ground motion to minimize the scatter in the results of nonlinear dynamic analysis. The first modification is based on ASCE 7-10 procedure. In this method, scaling of the acceleration response spectrum of ground motion is performed on appropriate acceleration histories that shall be obtained from records of events having magnitudes, fault distances, and source mechanisms that are consistent with those that control the maximum considered earthquake. The ground motions are scaled such that the average value of the 5 percent damped response spectra for the suite of motions is not less than the design response spectrum of the site in the neighborhood of the considered structural period.

The second modification method is based on the Conditional Mean Spectrum (CMS). The CMS provides the expected (i.e., mean) response spectrum, conditioned on occurrence of a target spectral acceleration value at the period of interest. Each ground motion is scaled so that the average response spectrum over the periods of interest is equal to the average of the target spectrum over the same periods.

The third modification procedure of ground motion records is called the Uniform Design Method (UDM). In this method a scale factor is produced for each different earthquake by tuning the response spectrum such that it results in a designed structure having a same period as the code-based designed structure.

2.1. Modification Based on ASCE 7-10

Like many seismic codes, the ASCE 7-10 code presents specific requirement for scaling of the acceleration response spectrum of the ground motion at hand. According to ASCE 7-10, a pair of recorded horizontal components of an earthquake should be used for analysis. The earthquake motion must be selected from those with magnitude, fault distance and fault mechanism consistent with the maximum expectable earthquake at the site. For each pair of the horizontal components, an SRSS acceleration response spectrum must be calculated for a damping ratio of 5%. The scale factor is a numerical coefficient multiplied to the SRSS spectrum such that the resulting modified spectrum just touches the design spectrum from above in the period range of 0.2T – 1.5T, where T is the fundamental period of the structure subjected to dynamic analysis. The same scale factor is also multiplied to the time histories of the ground motion. When several earthquakes are to be used, a common scale factor is calculated as described above for the average spectrum of SRSS spectra of different earthquakes.

2.2. Modification Based on Conditional Mean Spectrum (CMS)

The Conditional Mean Spectrum (CMS) is a rather new and much effective concept in scaling of ground motions. In this method, first a CMS as defined below, is constructed. Then it is used as a target spectrum to modify individual ground motion.

To construct a CMS, a key parameter ε as the spectral distance between the record at hand and the target spectrum at a certain period is used.

Modification of ground motion based on the CMS is implemented by calculating a scale factor as the ratio of the average of the target spectrum at the considered periods to the average of the response spectrum at the same periods:

$$\text{Scale Factor} = \frac{\sum_{j=1}^{n} Sa_{CMS}(T_j)}{\sum_{j=1}^{n} Sa(T_j)} \tag{7}$$

Such a modification makes the response spectra have a good resemblance with the CMS. In the above equation, $\sum_{j=1}^{n} Sa_{CMS}(T_j)$ is the sum of spectral accelerations of the CMS, and $\sum_{j=1}^{n} Sa(T_j)$ is the sum of spectral accelerations of the response spectrum for the period interval considered. In this method, each record will have a specific scale factor.

2.3. Modification Based on the Uniform Design Method (UDM)

The Uniform Design Method (UDM) is a new ground motion scaling method presented in this research. It will be shown that this method, retaining enough simplicity for use, has a superior behavior regarding dispersion in statistical responses.

The UDM introduces a certain scale factor for each different earthquake as follows. First the structure under study is designed for the unmodified response spectrum of the considered earthquake. The fundamental period of this structure is T_1^e. The same structure is again designed for the code-based design spectrum. The fundamental period of such a building is called T_1^{code}. In general $T_1^e \neq T_1^{code}$. For a constant structural mass, period is only a function of stiffness. To have a uniform design under different earthquakes and under the design spectrum, the following scale factor is introduced for each ground motion time history:

$$\text{Scale Factor} = \left(\frac{T_1^e}{T_1^{code}}\right)^2 \tag{8}$$

Where T_1^e and T_1^{code} as defined above are the fundamental periods of the building designed under the earthquake response spectrum and the design spectrum, respectively.

2.4. Characteristics of the Structure Studied

In this research a 5-story moment resisting steel structure with residential usage was designed according to IBC 2009, AISC2010 and ASCE 7-10. The building has three bays in both directions, each bay spanning 5m. Floor to floor heights are uniformly 3 m making a 15 m high building with an area totaling 1125m^2. The structure was designed using the modal spectrum analysis for lateral loading and the LRFD for member design, resulting in W sections for beams and Box sections for columns. The design spectrum is that of ASCE 7-10 for a site class C in California with $S_{D1} = 1$ and $S_{DS} = 0.52$. The fundamental period of the building is T=0.96.

2.5. Modification of the Accelerograms

2.5.1. ASCE 7-10 scaling

The methodology described in last sections is used to scale the records based on ASCE 7-10. The period range of scaling, 0.2 T to 1.5T, is 0.19 – 1.44. The scale factor such calculated is 4.999 for ASCE 7-10 method.

2.5.2. CMS scaling

As explained in last sections, the CMS scaling requires first a target CMS spectrum to be constructed from a response spectrum and then the scale factor to be calculated from Eq. (1). In this section the similarly calculated scale factors for other records are presented in Table 4.

Table 4. Scale factors of individual records based on CMS.

Event	Station	Scale Factor
Earthquakes	NGA1007	1.07550295
	NGA0993	1.143820225
	NGA0070	1.417919345
	NGA1005	1.334503522
	NGA1057	1.587214968
	NGA1031	1.50729184
	NGA1008	1.629109255
	NGA0078	1.671342755
	NGA0991	1.463334115
	NGA1035	1.57304489

2.5.3. UDM scaling

As described in last section, with UDM, the building is designed with the response spectrum of each earthquake and its fundamental period, T_1^e, is calculated in each case. Similarly, T_1^{code} is determined for the building designed with the design spectrum. For the building described, $T_1^{code} = 0.96\ \mathrm{sec}$. Then the scale factor for each earthquake record is calculated from Eq. (3). The results are shown in Table 2.

Table 5. Scale factors of individual records based on UDM.

Event	Station	Scale Factor
Earthquakes	NGA1007	1.835889383
	NGA0993	1.31156627
	NGA0070	1.1
	NGA1005	2.080784907
	NGA1057	2.318158984
	NGA1031	3.065938328
	NGA1008	2.662444001
	NGA0078	1.915570989
	NGA0991	2.328891324
	NGA1035	2.054070274

3. DYNAMIC RESPONSE ANALYSIS

Nonlinear dynamic response of the building is calculated in this section under the earthquake records scaled. The beams and columns of the structure are modeled using elasto-plastic hinges concentrated at both ends of members. The response functions of interest are maximum base shear and lateral roof displacement. Mean and C.O.V. of each function is also calculated and used for comparison. No collapse is observed under either of scaled earthquakes. Responses of the structure with the three different scaling methods described above have been calculated. Table 4 shows the average responses along with the coefficient of variation (C.O.V.) for each scaling method, for the earthquake.

Table 6. Summary of structural response results

Method	Base shear (Kg)		Roof Displ, (Cm)	
	Average	C.O.V	Average	C.O.V
ASCE 7-10	513949.694	0.1852	18.79	0.2892
Conditional Means Spectrum	381243.317	0.1453	13.81	0.2147
Uniform Design Method	385768.607	0.0936	13.495	0.1942

As is apparent, while in some cases, not always, the CMS method has resulted in less scatter in nonlinear responses, the UDM has a much less C.O.V. in all cases. Therefore, scaling of seismic records with the UDM results in more confidence in responses when implementing nonlinear dynamic analysis.

4. CONCLUSIONS

An effective selection and modification of ground motion as the loads to be used in the analysis can lead to responses with low dispersion in nonlinear structural analysis. This in turn, results in much more trust in the safety of the designed structure. The accelerograms were scaled according to three different methods, namely, those of ASCE 7-10, Conditional Mean Spectrum (CMS), and the new method proposed in this research and called the Uniform Design Method (UDM). A 5-story AISC steel structure was used as a prototype for calculations.

While the scale factors varied largely between the different methods, the average of global structural responses including the base shear and the roof displacement were not as much. On the other hand, the proposed procedure of UDM for scaling of ground motions resulted in the least coefficient of variation in nonlinear response of the structure studied. Therefore, the proposed method results in more reliable results with less dispersion when implementing a nonlinear dynamic analysis.

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