An Improved Method for Nonstationary Spectral Matching

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Seismic input to nonlinear dynamic analyses of structures is usually defined in terms of acceleration time series whose response spectra are compatible with a specified target response spectrum. Time domain spectral matching used to generate realistic design acceleration time series is discussed in this paper. A new and improved adjustment function to be used in modifying existing accelerograms while preserving the nonstationary character of the ground motion is presented herein. The application of the new adjustment wavelet ensures stability, efficiency and speed of the numerical solution and prevents drift in the resulting velocity and displacement time series. [DOI: 10.1193/1.3459159]

INTRODUCTION

Seismic design of structures is generally based on a design response spectrum obtained from hazard analysis for a specified return period. The disaggregation of the hazard is then used to determine the controlling earthquake scenario in terms of magnitude and distance. For many engineering applications, such as the design of critical facilities or highly irregular buildings, a more complex dynamic nonlinear analysis is often conducted. Such analysis requires input in the form of design time series with response spectra that are consistent with the target design spectrum.

Design time series are developed by modifying initial time series that consist of empirical recordings from past earthquakes representative of the design event or numerical simulations of the ground motion for the design event. Two approaches exist for modifying the time series to be consistent with the design response spectrum: scaling and spectral matching. Scaling involves multiplying the initial time series by a constant factor so that the spectrum of the scaled time series is equal to or exceeds the design spectrum over a specified period range. Spectral matching involves modifying the frequency content of the time series to match the design spectrum at all spectral periods.

Although spectral matching is commonly used in engineering practice, the concept of using spectrum compatible time series in the seismic design of structures remains controversial for two reasons. First, a time series that matches the entire design spectrum represents more than one earthquake at a time since the design spectrum may be an envelope of multiple earthquakes. As a result, it is generally believed that such time series overestimate the structural response. Second, spectrum compatible time series have

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smooth response spectra and are considered unrealistic when compared to typical earthquake response spectra that tend to have large peaks and troughs.

The advantage of using spectrum compatible time series is to reduce the number of time series that need to be run in the engineering analysis. A gross rule of thumb is that one spectrum compatible time series is worth three scaled time series in terms of the variability of the mean of the nonlinear response of structures (Bazzurro and Luco 2006). For example, if it takes engineering analyses of nine scaled time series to get 20% accuracy in the mean structural response, then it takes only analyses of three spectrum compatible time series to get the same accuracy. If time series analyses are expensive, then there can be a significant cost saving using the spectrum compatible approach. An important additional benefit of the spectral matching approach is that the criteria for selecting the initial time series are not as stringent as those for the scaling approach. For example, if the design ground motion is for rock site conditions, initial time series on deep soil sites can be used because the spectral matching process will correct for the differences in frequency content on soil and rock sites. Adopting the spectral matching approach, therefore, results in more choices for the initial time series selection compared to the scaling approach.

Various methods have been developed to modify a reference time series so that its response spectrum is compatible with a specified target spectrum. A review of spectral matching methods is given by Preumont (1984). There are three basic approaches for spectral matching: frequency domain method, frequency domain method with random vibration theory (RVT), and time domain method. Early spectral matching approaches used the frequency domain method. This method adjusts the Fourier amplitude spectrum based on the ratio of the target response spectrum to the time series response spectrum while keeping the Fourier phase of the reference time series fixed. While this approach is straightforward, it has two drawbacks. First, it generally does not have good convergence properties. Second, it often alters the nonstationary character of the time series to such a large degree that it no longer looks like a time series from an earthquake. The second approach uses random vibration theory to make initial large adjustments to the Fourier amplitude spectrum, followed by the frequency domain method for small-scale adjustments. This method generally works well in terms of the acceleration and velocity time series, but often changes the character of the displacement time series.

The third approach for spectral matching adjusts the time series in the time domain by adding wavelets to the initial time series. A formal optimization procedure for this type of time domain spectral matching was first proposed by Kaul (1978) and was extended to simultaneously match spectra at multiple damping values by Lilhanand and Tseng (1987, 1988). While the time domain spectral matching procedure is generally more complicated than the frequency domain approach, it has good convergence properties and in most cases preserves the nonstationary character of the reference time series.

While the original Lilhanand and Tseng algorithm uses an adjustment wavelet that ensures numerical stability of the time domain spectral matching method, their adjustment function does not preserve the nonstationary character of the initial acceleration time series and introduces drift to the resulting velocity and displacement time series. Abrahamson (1992) developed the RspMatch program to implement the Lilhanand and Tseng algorithm and proposed a new adjustment wavelet that preserves the nonstationary character of the reference ground motion and ensures stability and efficiency of the numerical solution. This adjustment wavelet, however, does not integrate to zero end velocity and displacement and leads to drift in the resulting velocity and displacement time series. The original RspMatch program, therefore, requires the application of a baseline correction to the resulting acceleration time series to correct for the drift in the corresponding velocity and displacement time series. Hancock et al. (2006) revised and cleaned RspMatch to eliminate this drift by modifying the adjustment wavelets. The adjustment functions proposed by Hancock et al. (2006) and used in their updated version of RspMatch (2005) consist of the original functions developed by Abrahamson (1992) and Suarez and Montejo (2003, 2005) modified to include the baseline correction in their functional form. As a result, analytical solution of the problem is no longer possible and numerical speed and efficiency is compromised by the use of numerical integration. Moreover, additional wavelets are sometimes needed in RspMatch2005 to prevent divergence of the solution. These wavelets, nevertheless, sometimes have limited success in ensuring solution convergence. Hancock et al. (2006) also allowed acceleration records to be matched to a pseudo-acceleration target spectrum with different levels of damping simultaneously.

In this paper, we propose a new adjustment function that allows the use of an analytical solution in the spectral matching algorithm and that readily integrates to zero velocity and displacement without adding baseline correction to its functional form. The new version of RspMatch, described herein, provides a stable and time-efficient solution without introducing drift to the resulting velocity and displacement time series. It also allows matching records to pseudo-acceleration response spectra and ensures convergence and stability of the solution.

METHODOLOGY FOR TIME DOMAIN SPECTRAL MATCHING

The algorithm proposed by Lilhanand and Tseng (1987, 1988) and implemented in RspMatch uses wavelet functions to modify the initial time series such that its response spectrum is compatible with the design spectrum. A fundamental assumption of this methodology is that the time of the peak response does not change as a result of the wavelet adjustment. If $a(t)$ is the initial acceleration time series, the goal is to modify $a(t)$ such that its computed response spectrum matches the target spectrum across the whole frequency range while maintaining realistic velocity and displacement time series.

The difference between the target spectrum and the time series spectrum at a given frequency (ω_i) and damping (β_i), called the spectral misfit, is given by

$$\Delta R_i = (Q_i - R_i)P_i, \tag{1}$$

where Q_i is the target spectral value, R_i is the time series spectral value, and P_i is the polarity of the peak response of the oscillator. P_i is equal to 1 if the maximum oscillator response is positive and P_i is equal to −1 if the maximum oscillator response is negative.

Assuming that the time of the peak oscillator response, t_i, will not be perturbed by adding a small adjustment to $a(t)$, the basic method is to determine an adjustment time series, $\delta a(t)$, such that the oscillator response from $\delta a(t)$ at time t_i is equal to ΔR_i for all i. $\delta a(t)$ can be written as

$$\delta a(t) = \sum_{j=1}^{N} b_j f_j(t), \tag{2}$$

where $f_j(t)$ is a set of adjustment functions, b_j is the set of amplitudes of the adjustment functions (coefficients to be determined), and N is the total number of spectral points (frequency and damping pairs) to match. The acceleration response of $\delta a(t)$ for frequency ω_i and damping β_i at time t_i is given by

$$\delta R_i = \int_0^\infty \delta a(\tau) h_i(t_i - \tau) d\tau, \tag{3}$$

where $h_i(t)$ is the acceleration impulse response function for a single-degree-of-freedom oscillator with frequency ω_i and damping β_i, and τ is the integration time parameter. Substituting Equation 2 into Equation 3 gives

$$\delta R_i = \sum_{j=1}^{N} b_j \int_0^\infty f_j(\tau) h_i(t_i - \tau) d\tau. \tag{4}$$

The acceleration impulse response function is given by

$$h_i(t) = \frac{-\omega_i}{\sqrt{1-\beta_i^2}} \exp(-\omega_i \beta_i t)\left[(2\beta_i^2 - 1)\sin(\omega_i' t) - 2\beta_i \sqrt{1-\beta_i^2}\cos(\omega_i' t)\right], \tag{5}$$

where

$$\omega_i' = \omega_i \sqrt{1-\beta_i^2}, \tag{6}$$

and $h_i(t)=0$ for $t<0$. Let c_{ij} be the response at time t_i for the ith frequency and damping resulting from the adjustment function $f_j(t)$, then

$$c_{ij} = \int_0^{t_i} f_j(\tau) h_i(t_i - \tau) d\tau. \tag{7}$$

Substituting Equation 7 into Equation 4 gives

$$\delta R_i = \sum_{j=1}^{N} b_j c_{ij}. \tag{8}$$

If the response of the adjustment time series, δR_i, is equal to the spectral misfit, ΔR_i, then

$$\Delta R_i = \sum_{j=1}^{N} b_j c_{ij}. \tag{9}$$

The amplitude of each wavelet used in the adjustment is determined by

$$\mathbf{b} = \mathbf{C}^{-1} \boldsymbol{\delta} \mathbf{R} \tag{10}$$

where **C** is a square matrix with elements describing the amplitude of each single degree of freedom response at the time the response needs to be adjusted, under the action of each wavelet.

Given b_j, the adjustment time series, $\delta a(t)$, can be computed using Equation 2. The new adjusted time series for the first iteration is given by

$$a_1(t) = a(t) + \gamma \delta a(t), \tag{11}$$

where γ is a relaxation parameter (between 0 and 1) to damp the adjustments. In the second iteration, the algorithm is repeated using the adjusted time series, $a_1(t)$, in place of $a(t)$. The iterations are continued until the desired accuracy of the spectral match is achieved.

SELECTION OF INITIAL TIME SERIES

Ideally, time series having the same source, path, and site properties as the design earthquake should be selected. These properties include earthquake magnitude, distance, style-of-faulting, directivity condition, and site condition. Typically, there are not enough recordings in the empirical strong motion database to satisfy all of these conditions. The alternatives are to use numerical simulations that have all of the desired features or to relax some of these conditions to get enough candidate recordings.

Artificially generated spectrum compatible ground motions are the result of numerical simulations that can include detailed modeling of rupture propagation, path and site effects. The disadvantage of using such ground motions is that there is less confidence that they capture important features in the nonlinear analysis of structures. As a result, the use of empirical recordings, whenever possible, is generally preferred over the use of artificially generated spectrum compatible ground motions.

In selecting empirical recordings, the key parameters that affect the nonstationary character of the wave form are magnitude, distance, and directivity direction (for sites located close to large faults). Magnitude is the first parameter that should be included in defining the search window. Whenever possible, recordings should be within 0.5 magnitude units of the design earthquake. Depending on the size of the event, it may be possible to restrict the magnitude to a tighter range (such as within 0.25 magnitude units). Source to site distance should be restricted to be within ±10 km in the near fault region but can be extended to be within ±20 km at larger distances from the fault. Site condition has a strong influence on the frequency content of ground motions. It is, therefore, an important parameter for the scaling approach but not as important for spectral matching as long as extreme effects such as soft soil sites are excluded. Directivity effects are an important parameter in the selection of initial time series. If near-source effects are a factor in the design, the selection of initial time series should identify records at short distances and in the forward directivity zone. Finding a record with the same style-of-faulting as the design earthquake is not an important criterion in the initial time series selection.

If multiple recordings are used, they should be selected such that they have a range of nonstationary characteristics sampling the range of ground motions. This can be accomplished by selecting recordings from multiple earthquakes and/or multiple azimuths (e.g., directivity directions) for a single earthquake.

ADJUSTMENT FUNCTIONS

The Lilhanand and Tseng algorithm provides a good solution to the spectral matching problem but suffers from two shortcomings. First, the adjustment wavelets corrupt the velocity and displacement time series of the computed accelerograms by introducing a long period drift. Baseline correction is therefore needed to correct this resulting drift in the displacement time series. Second, the method is not always stable and diverges if matching of closely spaced periods and multiple damping levels is attempted. The new version of RspMatch presented in this paper addresses these shortcomings and improves the stability and efficiency of the algorithm.

The key to the non-stationarity of the Lilhanand and Tseng method is the selection of the adjustment function $f_j(t)$. The adjustment function should be selected to yield realistic spectrum compatible acceleration time series. The numerical stability and speed of the algorithm must also be considered when selecting the form of $f_j(t)$. For the method to work efficiently, the timing of $f_j(t)$ should be such that the response of $f_j(t)$ is in phase with the peak response of $a(t)$. For numerical speed, $f_j(t)$ should be chosen such that the elements of **C** given by the integral in Equation 7 can be computed analytically. For numerical stability, the off-diagonal terms of **C** should be as small as possible. Two alternative models for the adjustment function used in the original version of RspMatch are discussed in this section. The improved adjustment wavelet proposed by the authors is also presented.

WAVELET USED BY LILHANAND AND TSENG

The original wavelet used by Lilhanand and Tseng (1987, 1988) consists of the true acceleration impulse response function in reverse time order given by

$$f_j(t) = h_j(t_j - t) = \frac{-\omega_j}{\sqrt{1-\beta_j^2}}\exp(-\omega_j\beta_j(t_j - t))[(2\beta_j^2 - 1)\sin(\omega_i'(t_j - t)) \\ - 2\beta_j\sqrt{1-\beta_j^2}\cos(\omega_j'(t_j - t))], \tag{12}$$

where t_j is the time of the peak response of the j^{th} oscillator under the action of the j^{th} wavelet. An example of this wavelet form is shown in Figure 1.

The wavelet form used by Lilhanand and Tseng has several desirable numerical features that help keep the solution algorithm stable. First, it leads to a symmetric **C** matrix. Second, the abrupt stop insures that the response will peak at time t_j and will not reso-

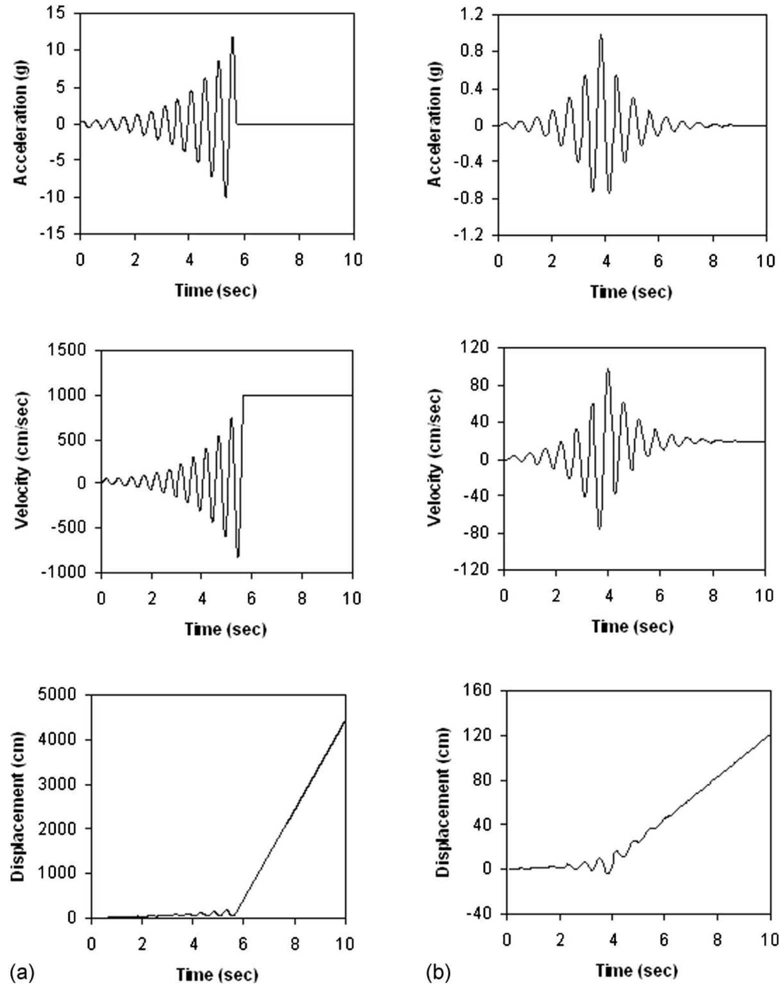

Figure 1. Acceleration, velocity, and displacement time series of (a) reverse acceleration impulse response wavelet and (b) tapered cosine wavelet.

nate to larger values at greater values of t. The desirable numerical features of this model lead to some undesirable features from a seismological point of view, particularly at long periods. As shown in Figure 1, the adjustment is emergent and stops abruptly. This is contrary to the behavior of strong motion time series that generally have a sharp initiation and gradual decay. Moreover, the adjustment function is non-zero only before the time of the peak response which can lead to unrealistic time series. For example, forcing the long period adjustment early in the time series can lead to unrealistic ground motions if the long period response peaks early in the record as can be the case for near-fault recordings with distances less than 5 km. Finally, the reverse acceleration impulse response wavelet introduces drift to the velocity and displacement time series as seen in Figure 1. This drift requires the application of baseline correction to the resulting time series after each iteration which can partially undo the spectral match and is time-consuming.

TAPERED COSINE WAVELET

The tapered cosine wave shown in Figure 1 can be described by

$$f_j(t) = \cos[\omega'_j(t - t_j + \Delta t_j)]\exp[-|t - t_j + \Delta t_j|\alpha_j], \tag{13}$$

where Δt_j is the difference between the time of peak response t_j and the reference origin of the wavelet. Δt_j is given by

$$\Delta t_j = \frac{\tan^{-1}\left[\frac{\sqrt{1-\beta_j^2}}{\beta_j}\right]}{\omega'_j}. \tag{14}$$

α_j is a frequency-dependent factor that should be selected such that the adjustment wavelet and the reference time series have consistent durations at frequency ω_j. In other words, if the reference time series has a short duration at a particular frequency, α_j should be selected such that the adjustment function at that frequency will also have a short duration (Hancock et al. 2006). A tri-linear model for $\alpha(f)$ is given by

$$\begin{aligned} \alpha(f) &= a_1 f && \textit{for } f < f_1 \\ \alpha(f) &= \left(a_1 + (a_2 - a_1)\frac{(f - f_1)}{(f_2 - f_1)}\right) f && \textit{for } f_1 < f < f_2 \\ \alpha(f) &= a_2 f && \textit{for } f > f_2. \end{aligned} \tag{15}$$

The use of the tapered cosine wave as an adjustment function has the advantage of preserving the nonstationary character of the acceleration time series. However, this adjustment function introduces drift to the velocity and displacement time series as shown in Figure 1. This drift is due to the functional form of the adjustment function and not to numerical errors. It requires applying baseline correction to the adjusted acceleration time series.

IMPROVED TAPERED COSINE WAVELET

In order to prevent drift in the adjusted velocity and displacement time series, an adjustment wavelet was chosen such that its functional form integrates to zero velocity and displacement. Moreover, to ensure speed and efficiency of the solution, the adjustment function was chosen such that the elements of the **C** matrix can be computed analytically. The improved adjustment function therefore consists of a cosine function tapered with a Gaussian function. The improved tapered cosine wavelet differs from the corrected tapered cosine wavelet proposed in Hancock et al. (2006) in that the wavelet presented herein has a functional form that readily integrates to zero velocity and displacement without including any baseline correction in its functional form. Contrary to the wavelets proposed in Hancock et al. (2006), the improved tapered cosine wavelet

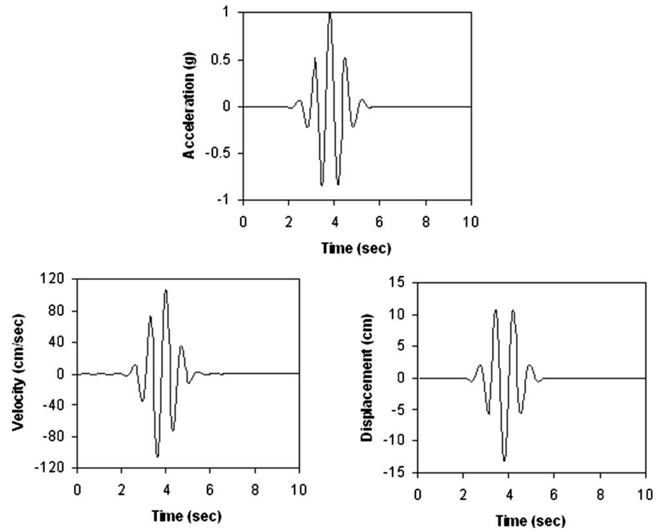

Figure 2. Acceleration, velocity and displacement time series of the improved tapered cosine wavelet.

allows the elements of the **C** matrix given in Equation 7 to be determined analytically, ensuring speed, stability, and efficiency of the solution. The improved tapered cosine wavelet, shown in Figure 2, can be described by

$$f_j(t) = \cos[\omega_j'(t - t_j + \Delta t_j)]\exp\left[-\left(\frac{t - t_j + \Delta t_j}{\gamma_j}\right)^2\right], \tag{16}$$

where γ_j is a frequency dependent coefficient used to adjust the duration of the adjustment function. $\gamma(f)$ was developed to ensure a smooth taper that would include several cycles in the adjustment function and would therefore lead to zero velocity and displacement at all frequencies. $\gamma(f)$ is given by

$$\gamma(f) = 1.178f^{-0.93} \tag{17}$$

The advantage of using the Gaussian taper in the adjustment wavelet is that it is smooth and continuous. As a result, the wavelet ends with zero velocity and displacement as shown in Figure 2 and no drift appears in the velocity and displacement time series of the adjusted ground motion.

IMPROVED SOLUTION PROCEDURE

The spectral matching program, RspMatch, was revised to implement the new tapered cosine wavelet and improved to ensure the stability and efficiency of the solution. Moreover, the improved spectral matching method has the advantage of preserving fling in the acceleration time series. A flow chart presenting the spectral matching procedure as employed in the original version of RspMatch is presented in Hancock et al. (2006). The program's main features and workflow are largely unchanged in the new version presented herein except for what is mentioned below.

In the original version of RspMatch, the user needs to run the program different times for the same record and target spectrum in order to match different frequency ranges of the spectrum. Following each run, the user is required to apply baseline correction to the resulting acceleration time series to correct for the drift in the velocity and displacement time series before using the resulting time series as input to the subsequent run. This process of applying baseline correction after each run is cumbersome and time-consuming when multiple runs are needed for the generation of one spectrum compatible time series. The application of the improved tapered cosine function results in acceleration time series that have zero final velocity and displacement. As a result, the new version of RspMatch requires the user to specify the number of runs and the frequency ranges for each run in the input file. The program will automatically output the results of all the runs, which makes the process of spectral matching significantly faster. Other features that were added to RspMatch are discussed in the following sections.

PSEUDOSPECTRAL ACCELERATION

For direct displacement-based design as well as the design of long-period structures, spectral displacements rather than spectral accelerations are required. Since spectral displacements are directly related to the pseudospectral accelerations, matching time series to a target pseudo-acceleration spectrum should be performed. The new version of RspMatch was, therefore, revised to allow pseudospectral matching. The original algorithm proposed by Lilhanand and Tseng (1987, 1988) was modified to use the pseudo-acceleration impulse response of a single-degree-of-freedom oscillator instead of the true acceleration impulse response presented in Equation 5. The pseudo-acceleration impulse response function used to determine the acceleration response of the adjustment time series $\delta a(t)$ is given by

$$h_i(t) = \frac{-\omega_i}{\sqrt{1-\beta_i^2}} \exp(-\omega_i \beta_i t) \sin(\omega_i' t) \tag{18}$$

DYNAMIC PADDING OF ACCELERATION TIME SERIES

The improved tapered cosine wavelet used in generating spectrum compatible acceleration time series results in no drift in the velocity and displacement time series when the duration of the wavelet is long enough such that it starts with zeroes. In such cases, the areas under the positive and negative cycles of the acceleration time series cancel out and drift is not observed in the resulting velocity and displacement records. This, however, depends on the time, t_j, at which the response of the acceleration time series peaks for a certain frequency and damping pair. The frequency-dependent coefficient of the improved tapered cosine function, γ_j, was selected to ensure that drift in the velocity and displacement time series of the wavelet does not occur for most t_j values at different frequencies. The minimum t_j values required to prevent drift at different frequencies are shown in Figure 3. When t_j is lower than the minimum value at a certain frequency, the

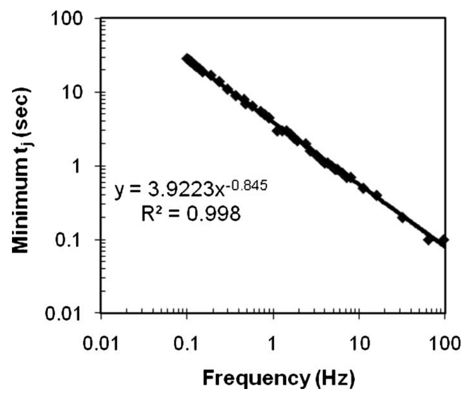

Figure 3. Relation between frequency and minimum t_j values.

improved tapered cosine wavelet does not start with zero and therefore does not integrate to zero velocity and displacement. For a frequency of 0.1 Hz, Figure 3 shows that drift occurs when t_j is less than 27.5 sec. The minimum t_j value required to prevent drift decreases as the frequency increases. For frequencies greater than 1 Hz, drift does not occur for t_j greater than about 2 sec.

In some cases, the response of the acceleration time series at low frequency peaks at t_j smaller than the minimum value defined in Figure 3. For such cases, the new version of RspMatch allows zero-padding the beginning of the acceleration time series such that t_j becomes equal to the minimum value at the specific frequency. The new version of RspMatch automatically checks that t_j value at a certain frequency is greater than the corresponding minimum value and zero-pads the beginning of the acceleration time series if necessary. This precludes any drift in the resulting velocity and displacement time series.

When the response of the acceleration time series peaks at high t_j values relative to the duration of the record, the improved tapered cosine wavelet does not end with zero. Although the spectrum compatible acceleration, velocity and displacement time series might end with nonzero values, drift does not occur for such cases. A taper can be applied outside RspMatch to bring the end of the resulting acceleration, velocity and displacement time series to zero.

EXAMPLE OF STEP-BY-STEP MATCHING PROCESS

Figure 4 shows the initial acceleration, velocity, and displacement of a recorded time series. The goal is to match the response spectrum of this initial time series, shown as the black line in Figure 5, to the target response spectrum, shown as the grey line in the same figure, while maintaining realistic and similar acceleration, velocity, and displacement profiles.

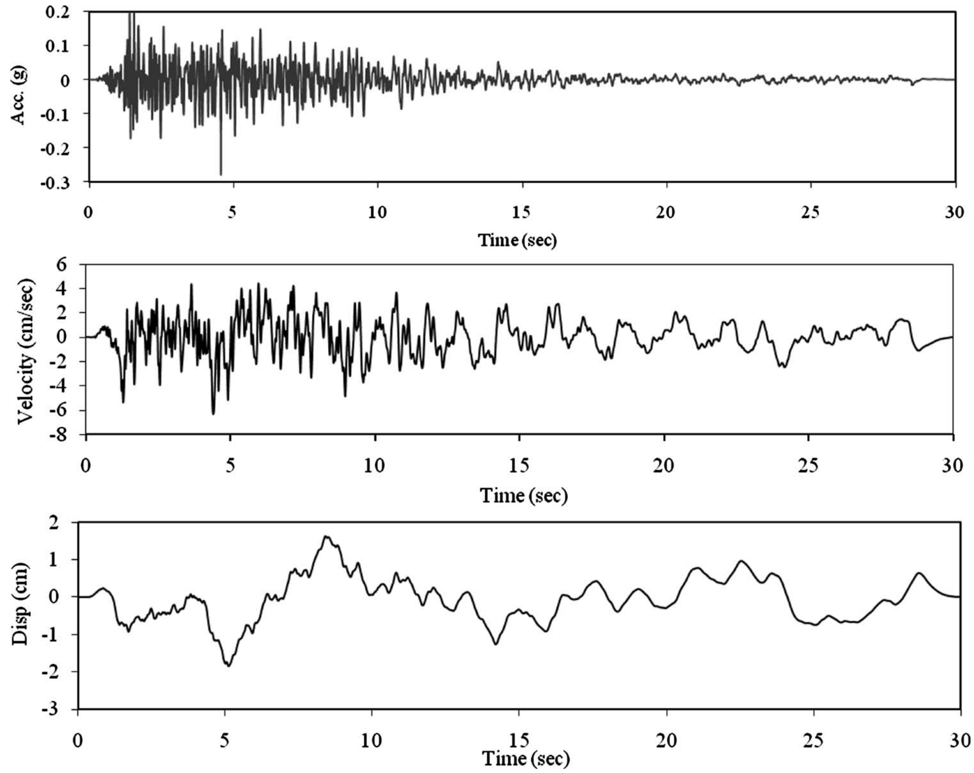

Figure 4. Initial acceleration, velocity, and displacement of a recorded time series.

Since the short period spectral acceleration is influenced by long period wavelets, only the short period range of the response spectrum is matched in the first pass. Matching the long period range of the response spectrum occurs in the next passes. In the first

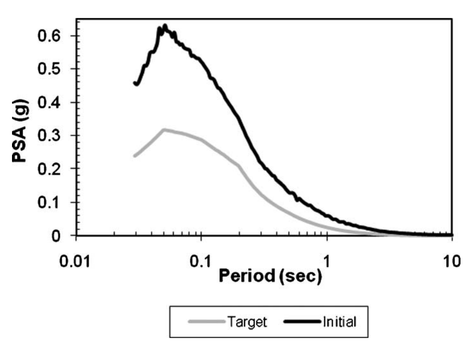

Figure 5. Initial response spectrum plotted against target response spectrum.

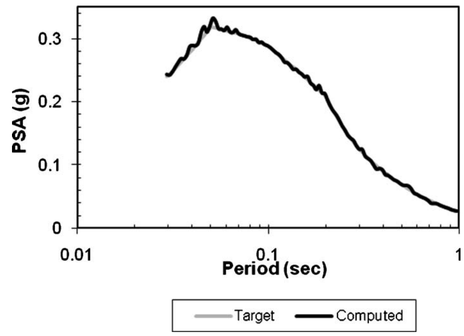

Figure 6. Response spectrum of the adjusted time series after the first pass plotted against target spectrum.

pass, the response spectrum is matched only up to a period of 1 sec. The initial spectral acceleration is scaled to match the target peak ground acceleration. The scaling flag is turned off for subsequent passes. As shown in Figure 6, the first pass brings the initial spectrum very close to target in the specified frequency range for matching (1 to 35 Hz for the first pass). The spectrum of the new adjusted time series is shown as the solid black line. The adjusted time series, which the new spectrum represents, is shown in the top frame of Figure 7. Note that the displacement profile of the adjusted time series, shown in the lower frame of the same figure, maintains the same general characteristics of the original recording shown in grey. No drift is observed in the velocity and displacement time series. Since the new spectrum is approaching the target spectrum and the characteristics of the new time series are consistent with the initial time series, we proceed to the second pass.

In the second pass, the spectrum is matched out to a period of 2 sec. Note that the period range for matching is extended out to longer periods progressively. The resulting spectrum from the second pass is a very good match to the target spectrum. The resulting velocity and displacement time series maintain the same general characteristics of the initial time series but have different amplitudes. This iterative process is carried out until the spectrum has been matched out to the desired period, in this case 10 sec. In Figure 8, we can see that this occurred on the fourth pass, where the new computed spectrum matches the target spectrum across the whole period range of interest. Checking the acceleration, velocity, and displacement profiles of the computed spectrum, Figure 9 shows that the nonstationary characteristics of the initial time series have been maintained. Though the amplitude and timing may be slightly off, the general characteristics of the initial time series have been preserved throughout the spectral matching process. We also note in Figure 9 that the adjusted time series are shifted to the right as a result of the zero-padding at the beginning of the acceleration time series.

As a final check, we compare the Fourier amplitude and the normalized Arias intensity of the initial time series and the final computed time series. In Figure 10, we see that the Fourier amplitude of the adjusted time series maintains the same general character-

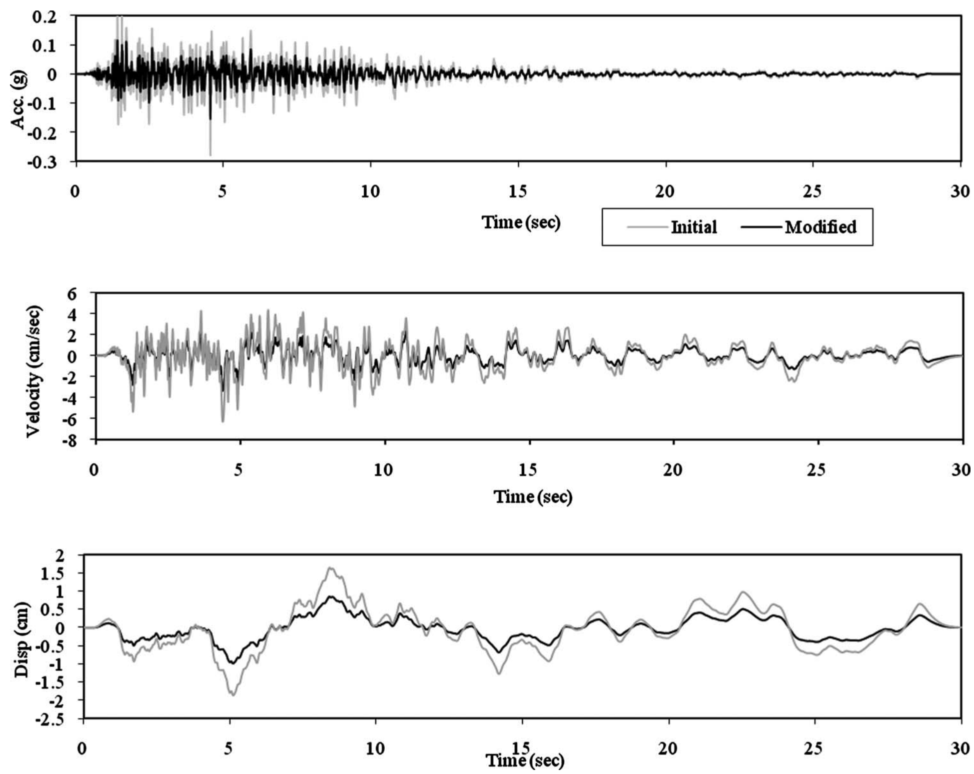

Figure 7. Acceleration, velocity, and displacement of the adjusted time series after the first pass plotted against the original time series.

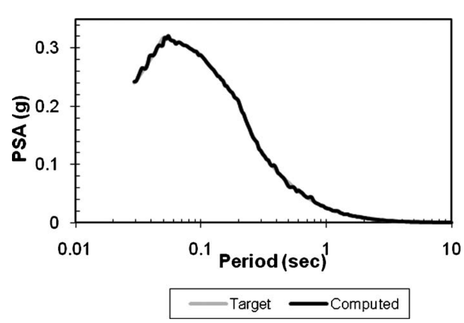

Figure 8. Response spectrum of the adjusted time series after the last pass plotted against target spectrum.

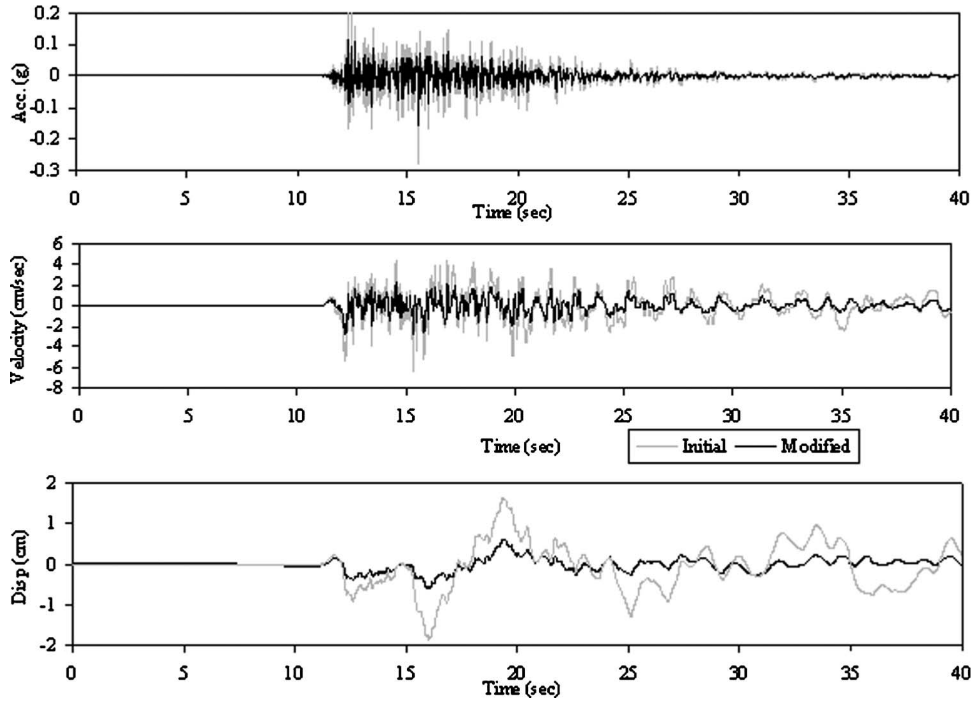

Figure 9. Acceleration, velocity, and displacement of the adjusted time series after the last pass plotted against the original time series.

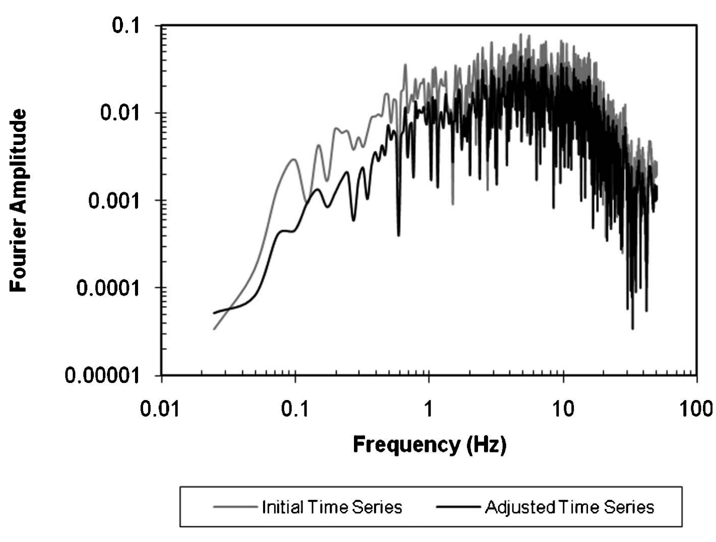

Figure 10. Comparison of the Fourier amplitudes of the initial and adjusted time series.

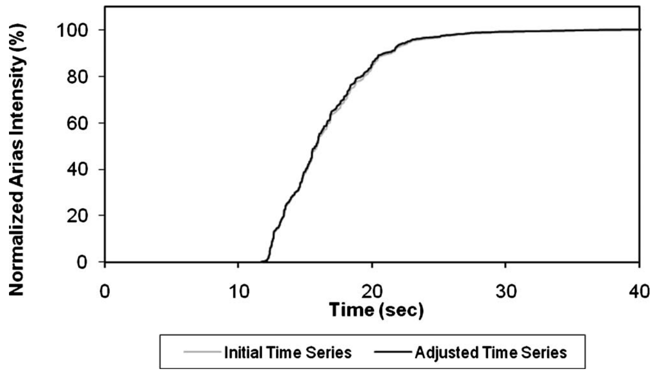

Figure 11. Comparison of the normalized Arias intensities of the initial and adjusted time series.

istics of that of the initial time series. Figure 11 shows a very small difference between the normalized Arias intensities of the original and the computed acceleration time series.

CONCLUSION

An improved method for the generation of spectrum compatible acceleration time series is presented in this paper. An improved tapered cosine wavelet has been developed for the adjustment of recorded ground motions resulting in acceleration time series that have no drift in the corresponding velocity and displacement profiles. As a result, the new method does not require baseline correction of the adjusted record after each pass. The application of the new wavelet ensures stability and convergence of the spectral matching solution. The spectral matching program, RspMatch, has been updated to implement the new wavelet solution. The new version of RspMatch enables records to be adjusted to target pseudospectral accelerations and allows zero-padding the beginning and/or the end of the initial record, if needed, to ensure zero final velocity and displacement. The new version of the program is available upon request from the corresponding author.

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