ON THE FITTING OF MULTIMODAL INTENSITY FUNCTIONS TO COMPLEX ACCELEROGRAMS

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ABSTRACT:

The estimation of the intensity function of an earthquake record is a key step for the non-stationary stochastic representation of seismic action in dynamic structural analyses. In spite of its importance, only a few procedures have been applied to obtain the intensity function of a given earthquake record. Amongst them, the underlying stationary process (USP) method, proposed by Ferrer and Sánchez-Carratalá (2006), is the only procedure that can be considered as a standard method for earthquake analysis, since it can be systematically applied to fit any prescribed intensity function to any real record. Furthermore, it allows the quantitative assessment of the fitting by using some error parameter calculated from the underlying process. The USP method has been extensively applied to many accelerograms from several seismic regions using common unimodal theoretical or code-based intensity functions. However, these unimodal functions only attempt to model the amplitude evolution over the time of seismic events caused by a singular and instantaneous rupture process. The analysis of complex accelerograms, with two or more separate peaks produced by several fault ruptures or very different wave paths, can be accomplished by the composition of two or more single-peak intensity functions. In the present paper, the standard USP method is extended to solve the problem of fitting the amplitude modulation function of multimodal accelerograms. A numerical application of the proposed method to some real multimodal earthquake records is carried out, showing the ability of the USP method to accurately obtain the amplitude modulation function of complex accelerograms.

KEYWORDS: earthquake record, intensity function, amplitude modulation function, multimodal accelerogram, non-stationary stochastic process, USP method

1. INTRODUCTION

The intensity function, also called the amplitude modulation function, represents the time variation of the standard deviation of a non-stationary process and, therefore, its calculation is necessary to represent a seismic event as a uniformly modulated evolutionary stochastic process. Moreover, the specification of an intensity function is essential for the simulation of synthetic accelerograms, or for the application of random vibration techniques to structural dynamics (Sánchez-Carratalá and Ferrer, 2004).

From a statistical point of view, a major drawback is found when trying to calculate the amplitude modulation function of a strong motion record, namely: a non-stationary process is inherently non-ergodic, and so the entire ensemble of realizations that constitute the process would be required to obtain the standard deviation function. Since only one record is usually available, the calculation of the intensity function becomes statistically impossible. However, the problem can be approximately solved by introducing some constraints in the procedure that are additional to the recorded data. Firstly, the general tendency of the standard deviation function can be found by identifying the main features of the earthquake record, i.e. rise time, strong motion duration, peak ground acceleration, etc. Furthermore, the functional shape of the intensity function is linked to the main seismogenetic features of the earthquake (location and directivity of the fault, crustal structure, etc.) and the local conditions of the recording site (geotechnical and topographic profile, impedance effects, etc.). Some theoretical intensity functions have been proposed in the scientific literature and seismic codes to roughly model the main characteristics of an earthquake record, as listed above (e.g. Shinozuka and Sato, 1967; Jennings *et al.*, 1968; Saragoni and Hart, 1974; Tung *et al.*, 1992; UNE-ENV 1998-2, 1998). Thus, the lack of statistical data in a single earthquake record may be partly compensated by the implicit seismic information found in these semiempirical intensity functions.

Several procedures have been used in the literature for the estimation of the amplitude modulation function (e.g. Cakmak *et al.*, 1985; Ólafsson, 1992; Spanos and Failla, 2004), but none can be considered as a standard method because of their inability to fit any prescribed theoretical or code-based intensity function to any accelerogram. Recently, Ferrer and Sánchez-Carratalá (2006) have proposed a general fitting method that iteratively searches for a target underlying stationary process (giving rise to the 'USP method' name) and using the least squares method as a basis. Due to the excellent performance of this fitting method when applied with unimodal intensity functions (Ferrer and Sánchez-Carratalá, 2006, 2007), its extension is proposed to the case of complex accelerograms, i.e. with two or more different portions of strong motion and where multimodal intensity functions composed of several unimodal intensity functions must be used. Below, a concise explanation of the application of the method in the multimodal case is presented, and a numerical application is carried out.

2. BASIS OF THE USP METHOD

The USP method assumes that the earthquake is adequately represented by a uniformly modulated evolutionary stochastic process (Priestley, 1965), so that:

$$a_g(t) = I_{ag}(t)\int_{-\infty}^{\infty} \exp(i\,2\pi f\,t)\,d\tilde{Z}(f) \tag{2.1}$$

where i is the imaginary unit, t is the time, f is the cyclic frequency, $\{a_g(t)\}$ is the non-stationary stochastic process that models the ground acceleration, $I_{ag}(t)$ is a real deterministic intensity function with a slow variation over time, and $\{\tilde{Z}(f)\}$ is a complex-valued stationary stochastic process with orthogonal increments. By applying the mathematical expectation operator to the function $a_g^2(t)$, and after performing some simple algebra, the following expression is obtained:

$$\sigma_{ag}^2(t) = I_{ag}^2(t)\,\sigma_{ag,s}^2 \tag{2.2}$$

where $\sigma_{ag}^2(t)$ is the variance function of the non-stationary process $\{a_g(t)\}$, and $\sigma_{ag,s}^2$ is the variance of the underlying stationary process $\{a_{g,s}(t)\}$, which has the following spectral representation:

$$a_{g,s}(t) = \int_{-\infty}^{\infty} \exp(i\,2\pi f\,t)\,d\tilde{Z}(f) \tag{2.3}$$

so that

$$a_{g,s}(t) = \frac{a_g(t)}{I_{ag}(t)} \tag{2.4}$$

The variance of an ergodic stationary process can be estimated from a discrete record by fitting a constant to the squared record using the least squares method. Ferrer and Sánchez-Carratalá (2006) extend this property to the case of a uniformly modulated non-stationary process by substituting the constant with a parametric function $C_{ag}(t)$ related with the intensity function by the following expression:

$$I_{ag}^2(t) \approx \frac{N}{N-1} C_{ag}(t) \tag{2.5}$$

where N is the number of points of the discrete record $a_g(t_i)$, with $t_i=i\Delta t$, $i=1,2,\ldots,N$, and Δt is the sampling time interval. The function $C_{ag}(t)$ need not be polynomial, so that the equations that minimize the error in the least squares method constitute, in general, a non-linear equation system and a numerical method must be applied to solve it (e.g. the Gauss-Newton method). In this paper, $\sigma_{ag,s}^2=1$ is assumed in Eqn. 2.2.

3. ERROR PARAMETER

Once the intensity function has been obtained, some error parameter should be defined to assess the quality of the fitting, or to compare different functions fitted to the same accelerogram. In accordance with the method described above, an error measurement of the fitting can be obtained from the analysis of the underlying stationary record, $a_{g,s}(t)$, assuming that it would be perfectly stationary if an ideal intensity function that exactly verifies Eqn. 2.2 were used in Eqn. 2.4. In practical applications, only a duration-limited underlying stationary record, $a_{g,sT}(t)$, is available, being T the time interval where $I_{ag}(t)$ is different from zero. Besides, only the portion of $I_{ag}(t)$ in which it more accurately represents the evolution of the standard deviation of the process, can be expected to give a sufficiently stationary record. Thus, a reliable underlying stationary record, $a_{g,s;r}(t)$, which corresponds to the most accurate portion of $a_{g,sT}(t)$, is defined. For typical semiempirical intensity functions, a stationary interval $\overline{T}$ that includes p=80~90% of the total energy released by the earthquake can be used.

Ferrer and Sánchez-Carratalá (2007) have proposed a new criterion to assess the degree of stationarity of the reliable underlying stationary record, which is based on the expected energy content evolution of the underlying stationary process. The Husid function (Husid *et al.*, 1969) of a stationary record $a_{g,s}(t)$ is:

$$H_{ag,s}(t) = \int_o^t a_{g,s}^2(u)\,du \tag{3.1}$$

The expected value of the Husid function of a stationary process of variance $\sigma_{ag,s}^2$ is:

$$E\left[H_{ag,s}(t)\right] = E\left[\int_o^t a_{g,s}^2(u)\,du\right] = \int_o^t E\left[a_{g,s}^2(u)\right]du = \int_o^t \sigma_{ag,s}^2 du = \sigma_{ag,s}^2 t \tag{3.2}$$

Therefore, the mean value of the Husid function of a stationary process is a linear function with a slope equal to the variance of the process. This property can be used to assess the stationarity of a record by comparing its Husid function (Eqn. 3.1) with the expected value of the Husid function for different times (Eqn. 3.2). So, an error parameter is defined as the coefficient of variation of $H_{ag,s}(t)$ in the stationary interval, i.e. the root mean square error of the Husid function $H_{ag,s}(t)$ with respect to its expected value $E[H_{ag,s}(t)]$, divided by the mean value of $E[H_{ag,s}(t)]$ in the stationary interval $\overline{T}$:

$$\varepsilon_{H,p} = \frac{2}{\overline{T}} \frac{\sqrt{\dfrac{\sum_{i=1}^{N'} \left(H_{ag,s}(t_i) - \sigma_{ag,s}^2 t_i\right)^2}{N'-1}}}{\sigma_{ag,s}^2} \tag{3.3}$$

where $\varepsilon_{H,p}$ is the so-called energy error, N' is the number of points of the discrete record $a_{g,s;r}(t_i)$ in the stationary interval $\overline{T}$, i.e. $\overline{T}$=N'Δt, and the subindex p indicates the percentage of energy released by the earthquake in the stationary interval. The quality of the fitting will improve as the value of $\varepsilon_{H,p}$ decreases, although small values of the error parameter can indicate that the process is almost stationary, as some fluctuations in the Husid function must be expected due to the randomness of a stochastic process.

4. IMPLEMENTATION OF THE USP METHOD

The application of the USP method to multi-peaked accelerograms follows the same procedure proposed by Ferrer and Sánchez-Carratalá (2006) for single-peak records. Obviously, some slight modifications and additions to the method must be made to take into account the complexity of the accelerogram. The multimodal intensity functions considered in this paper are composed by several Increasing-Peak-Decreasing (IPD) intensity functions (see Sánchez-Carratalá and Ferrer, 2004), since this would be the usual choice for fitting multi-peaked accelerograms, although ICD (Increasing-Constant-Decreasing) functions, or a mixture of both types, could also be used in general.

4.1. Previous operations

To apply the USP method, only the most significant part of the accelerogram $a_g(t)$ is considered. A windowed accelerogram ranging from t_1 to t_2 is obtained using the same procedure as in the case of unimodal functions (see Ferrer and Sánchez-Carratalá, 2006). In this paper, η_a=0.05 and η_b=0.01.

The number of modes, M, is estimated using the available seismic information or from a rational analysis of the accelerogram, so that the duration of each mode can be approximated as $T_m^{(0)} = t_{2,m}^{(0)} - t_{1,m}^{(0)}$, where $t_{1,m}^{(0)}$ and $t_{2,m}^{(0)}$, m=1,2,…,M, are the first guesses of, respectively, the initial and final instants of the mth mode, with $t_{1,m+1}^{(0)} = t_{2,m}^{(0)}$, m=1,2,…,M-1. The Husid function is then discretized with a constant relative increment Δh calculated with respect to its final value, $H_{ag}(t_2)$, so that the duration of each mode can be more accurately computed by searching the instants $t_{2,m}^{(1)}$ near $t_{2,m}^{(0)}$, m=1,2,…,M-1, in which the discretized Husid function changes its curvature from convex to concave. A good choice is $\Delta h \in [0.01,0.02]$. From now on, the intensity function of each mode is calculated by independently applying the USP method to each portion of the accelerogram defined by $t_{1,m}^{(1)}$ and $t_{2,m}^{(1)}$, m=1,2,…,M, with duration $T_m^{(1)} = t_{2,m}^{(1)} - t_{1,m}^{(1)}$.

4.2. Solution of the least squares equation

A smoothing process is carried out for each mode of the accelerogram, as in the case of unimodal intensity functions. This process produces a smoothed windowed record $a_{g;sw,m}(t)$ for each mode. In this paper, $\tau_{a,m}=(t_{max,m} - t_{1,m}^{(1)})/20$ is used for the width of the smoothing moving average window, where $t_{max,m}$ is the instant corresponding to the peak ground acceleration of the mth mode. Since the method to solve the equation system is iterative, an initial guess of the intensity function, $I_{ag,m}^{(0)}$, has to be given to start the solving process. The procedure is the same as for unimodal functions, but with the following differences: the initial time of the intensity function, $t_{0,m}$, is calculated as $t_{0,m}=t_{r,m}-c_4\,T_m^{(1)}$ (except for the first mode, where $t_{0,m}$, m=1, is defined as in the unimodal case), being $t_{r,m}$ the rise time of the intensity function corresponding to the mth mode; and the decreasing part of the function is forced through a point located at the instant $t_{5,m}=t_{2,m}$ (except for the last mode, where $t_{5,m}$, m=M, is obtained as in the unimodal case; see Ferrer and Sánchez-Carratalá, 2006). In this paper, c_4=0.15 is used.

Once $I_{ag,m}^{(0)}$ has been determined, the Gauss-Newton iterative method can be applied to solve the non-linear equation system, and a solution $I_{ag,m}^{(1)}$ is found.

4.3. Improvement of the fitting

In this step, the iterative algorithm defined by Ferrer and Sánchez-Carratalá (2006) is applied to each intensity function $I_{ag,m}^{(1)}$. However, a new condition must be introduced to guarantee the convergence of the iterative process, as some of the intensity functions $I_{ag,m}^{(1)}$, m=1,2,…,M, could be badly conditioned due to the probably higher levels of the accelerogram at intermediate times $t_{2,m}^{(1)}$, m=1,2,…,M-1. The condition consists of checking if the rise time of mth mode in the kth iteration, $t_{r,m}^{(k)}$, is inside the interval $[\,t_{r,m}^{(1)} \pm c_5 T_{ght;q,m}\,]$, where $T_{ght;q,m}$ is the total threshold duration of the mth mode (also called fractional or normalized duration) corresponding to a relative threshold level $q=\eta/a_{g;max,m}$, where $a_{g;max,m}$ is the peak ground acceleration of the mth mode of $a_g(t)$ (see Sánchez-Carratalá and Ferrer, 2004). In this paper, c_5=0.05 and q=0.05 are used.

Once the iterative process has finished, $I_{ag,m}^{(K^*)}$ is taken as the intensity function of the mth mode of the accelerogram, being K* the last iteration performed, or the iteration with the smallest stationarity error (for the definition of stationarity error, see Ferrer and Sánchez-Carratalá, 2006).

4.4. Composition of unimodal intensity functions

Steps 4.2 and 4.3 can be applied separately to all modes of the accelerogram, so that the different intensity functions $I_{ag,m}(t)$, m=1,2,…,M, are calculated. The intensity function of the complete accelerogram, $I_{ag}(t)$, is a piece-wise function obtained as the composition of the modal intensity functions $I_{ag,m}(t)$ between their intersection points, with the duration of each mode eventually defined as $T_m^{(2)} = t_{2,m}^{(2)} - t_{1,m}^{(2)}$, m=1,2,…,M, where $t_{1,m}^{(2)}$ and $t_{2,m}^{(2)}$ are the ultimate approach of, respectively, the initial and final instants of the mth mode, with $t_{1,m+1}^{(2)} = t_{2,m}^{(2)}$, m=1,2,…,M-1.

The goodness of the fitting is now evaluated using the energy error, $\varepsilon_{H,p}$. This error parameter is computed for each mode by applying Eqn. 3.3. The stationary interval of each mode, $\overline{T}_m$, is determined symmetrically from the Husid function of each mode, $H_{ag,m}(t)$, in such a way that $\overline{T}_m = t_{b,m}-t_{a,m}$, where $H_{ag,m}(t_{a,m})=(1-p)/2$ and $H_{ag,m}(t_{b,m})=(1+p)/2$. Finally, the error parameter in the whole record is computed as follows:

$$\varepsilon_{H,p} = \sum_{m=1}^{M} \varepsilon_{H,p,m} P_m \qquad (4.1)$$

where $\varepsilon_{H,p,m}$, m=1,2,…,M, is the energy error of the mth mode, and P_m, m=1,2,…,M, is the percentage of the total energy of the earthquake released during the mth mode.

5. NUMERICAL APPLICATION

In this paper, two corrected accelerograms provided by the European Strong-Motion Data project (ISESD, 2006) are used: the Campano-Lucano earthquake (Italy) of November 23, 1980 (M_w=6.9), and the Izmit-Kocaeli earthquake (Turkey) of August 17, 1999 (M_w=7.6). According to the remarks accompanying the downloaded records, the processing procedures applied are: linear baseline correction of acceleration and velocities, and an 8th order elliptical band-pass filter (0.25-25.00 Hz).

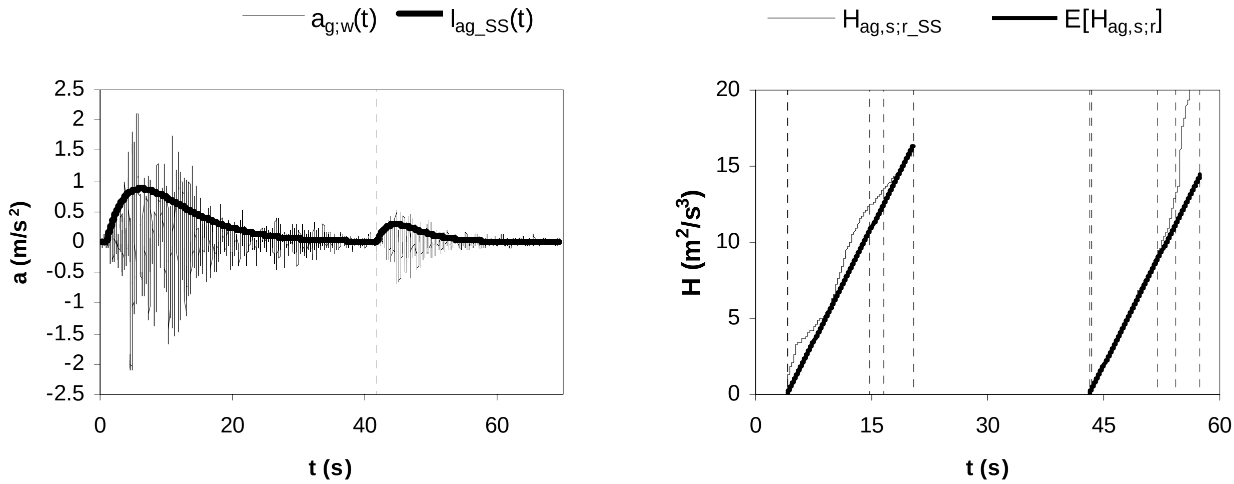

Figure 1. Left: Campano-Lucano earthquake record, and final fitting of the bimodal Shinozuka-Sato intensity function. Right: Comparison between the Husid function of the reliable underlying stationary record and the mean value of the Husid function of a stationary process of unit variance, for each mode.

The IPD functions fitted to obtain the multimodal intensity function of each earthquake record are: the exponential-exponential function of Shinozuka and Sato (1967) for the Italian earthquake, and the potential-exponential function of Saragoni and Hart (1974) for the Turkish earthquake.

5.1. Campano-Lucano earthquake

The accelerogram corresponds to the NS component recorded in the Sturno station at 23 km from the epicenter, with sampling time interval Δt=0.01 s, and peak ground acceleration $a_{g;max}$=2.12 m/s^2 (0.22g). According to Section 4.1, the duration of the windowed record, $a_{g;w}(t)$, is 69.42 s. The accelerogram has been divided into two modes using Δh=0.01, with $t^{(1)}_{1,1}=0$, $t^{(1)}_{2,1} = t^{(1)}_{1,2}=39.87$ s, and $t^{(1)}_{2,2}=69.42$ s.

The IPD Shinozuka-Sato (SS) intensity function has the following expression:

$$I_{ag\_SS}(t) = \begin{cases} 0 & t < t_0 \\ K_{SS}\left\{\exp\left[-a\,(t-t_0)\right]-\exp\left[-b\,(t-t_0)\right]\right\} & t_0 \le t \le T_{gt} \end{cases} \tag{5.1}$$

where K_{SS}, a, b and t_0 are the parameters of the intensity function, and T_{gt} is the duration of the fitted portion of the accelerogram.

The least squares method is applied to the initial guess of the intensity function for each mode with the additional restraint b≤2.50, which is introduced to avoid a small rise time ($t_r/T_{gt}\geq 0.05$). By applying the iterative algorithm of Section 4.3, the final estimate of the intensity function for each mode is obtained; the parameters are: for the first mode $I^{(3)}_{ag,1}$, $K_{SS,1}$=9476.5, a_1=0.1902, b_1=0.1903, and $t_{0,1}$=0.97 s; and for the second mode $I^{(3)}_{ag,2}$, $K_{SS,2}$=3677.3, a_2=0.3537, b_2=0.3538, and $t_{0,2}$=41.78 s.

In accordance with Section 4.4, the intersection point between the two modes occurs at the instant $t^{(2)}_{2,1} = t^{(2)}_{1,2}$=41.82 s. The fitted multimodal intensity function is shown in the left part of Fig. 1, along with the windowed record, $a_{g;w}(t)$; the discontinuous line indicates the intersection between both unimodal intensity functions. The energy error for each mode has been calculated as stated in Section 3, obtaining the following values: $\varepsilon_{H,85,1}$=0.1736 for the first mode, and $\varepsilon_{H,85,2}$=0.0834 for the second mode. By applying Eqn. 4.1

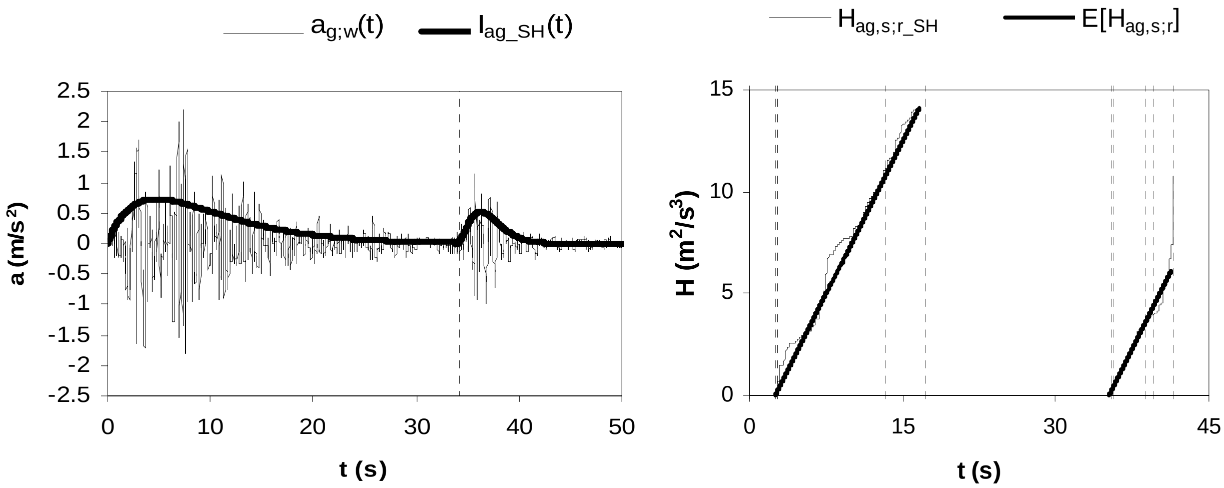

Figure 2. Left: Izmit-Kocaeli earthquake record, and final fitting of the bimodal Saragoni-Hart intensity function. Right: Comparison between the Husid function of the reliable underlying stationary record and the mean value of the Husid function of a stationary process of unit variance, for each mode.

$\varepsilon_{H,85}$=0.1683 is obtained for the complete accelerogram. In the right part of Fig. 1 the Husid function of the reliable underlying stationary record of each mode, $a_{g,s;r,m}(t)$, is represented, along with the expected Husid function; the discontinuous lines indicate the stationary intervals corresponding to the 80, 85, and 90% energy levels for each mode.

5.2. Izmit-Kocaeli earthquake

The accelerogram corresponds to the EW component recorded in the Izmit-Meteoroloji Istasyonu station at 9 km from the epicenter, with sampling time interval Δt=0.01 s, and peak ground acceleration $a_{g;max}$=2.19 m/s^2 (0.22g). According to Section 4.1., the duration of the windowed record, $a_{g;w}(t)$, is 51.65 s. The accelerogram has been divided into two modes using Δh=0.01, with $t_{1,1}^{(1)}=0$, $t_{2,1}^{(1)}=t_{1,2}^{(1)}$=31.10 s, and $t_{2,2}^{(1)}$=51,65 s.

The IPD Saragoni-Hart (SH) intensity function has the following expression:

$$I_{ag\_SH}(t)=\begin{cases}0 & t<t_0\\ K_{SH}\, t^m \exp\left[-a\,(t-t_0)\right] & t_0\le t\le T_{gt}\end{cases} \tag{5.1}$$

where K_{SH}, a, m and t_0 are the parameters of the intensity function, and T_{gt} is the duration of the fitted portion of the accelerogram.

The least squares method is applied to the initial guess of the intensity function for each mode with the additional restraint 0.185≤m≤2.70, which is introduced to avoid a small or large rise time ($0.05\le t_r/T_{gt}\le 0.30$). By applying the iterative algorithm of Section 4.3, the final estimate of the intensity function for each mode is obtained; the parameters are: for the first mode $I_{ag,1}^{(3)}$, $K_{SH,1}$=0.4331, a_1=0.1943, m_1=0.9317, and $t_{0,1}$=0 s; and for the second mode $I_{ag,2}^{(1)}$, $K_{SH,2}$=0.7071, a_2=1.1118, m_2=2.7000, and $t_{0,2}$=33.83 s.

In accordance with Section 4.4, the intersection point between the two modes occurs at the instant $t_{2,1}^{(2)}=t_{1,2}^{(2)}$=34.10 s. The fitted multimodal intensity function is shown in the left part of Fig. 2, along with the windowed record, $a_{g;w}(t)$; the discontinuous line indicates the intersection between both unimodal intensity functions. The energy error for each mode has been calculated as stated in Section 3, obtaining the following values: $\varepsilon_{H,85,1}$=0.0944 for the first mode, and $\varepsilon_{H,85,2}$=0.1873 for the second mode. By applying Eqn. 4.1 $\varepsilon_{H,85}$=0.1064 is obtained for the complete accelerogram. In the right part of Fig. 2 the Husid function of the reliable underlying stationary record of each mode, $a_{g,s;r,m}(t)$, is represented, along with the expected Husid function; the discontinuous lines indicate the stationary intervals corresponding to the 80, 85, and 90% energy levels for each mode.

6. CONCLUSIONS

The USP fitting method has been successfully extended to the case of complex accelerograms, i.e. seismic records with different strong motion parts, by fitting multimodal intensity functions composed of several unimodal IPD functions. The procedure consists of identifying the modes of the accelerogram, fitting a prescribed intensity function to each mode using the USP method, and, finally, joining all the unimodal functions with the condition that the intensity function of the whole accelerogram is continuous. The procedure has shown an overall good performance in numerical applications, so that the robustness, reliability, and precision of the USP method for the fitting of multimodal intensity functions to complex accelerograms have been evidenced.

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