The 14[th] World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

ANALYSIS OF NON-LINEAR DYNAMIC RESPONSE OF STRUCTUTRES SUBJECTED TO SYNTHETIC ACCELERATIONS

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ABSTRACT :

Studies of non linear structural response subjected to earthquake accelerograms have contributed significantly to the improvement of our understanding of the degradation process of structures during strong motion earthquakes. The knowledge of this degradation process can be used with efficiency in order to assess the time history response and the aseismic design of critical structures such as dams, nuclear power plants and other important facilities. The objective of this study is to identify the effects of the frequency nonstationarity, on the nonlinear structural response, by using a nonstationary stochastic model based on the concept of physical spectrum and simple inelastic structural models.The nonstationary stochastic model is used to simulate, two sets of artificial earthquakes compatible with a real ground acceleration record and exhibiting similar phases distribution [6] and different frequency contents. The first group presents a time varying frequency content and the second one group has a time invariant frequency content. Three hysteretic models have been considered. The variability of the maximum displacement ductility was represented in terms of probabilistic inelastic response spectra for the two groups of the precedent simulated accelerograms.

KEYWORDS: physical spectrum**,** time variant frequency, time invariant frequency, inelastic structures, ductility, moving resonance.

1. INTRODUCTION

Nonlinear structural response subjected to earthquake accelergorams have contributed significantly to the improvement of our understanding of the degradation process of structures during strong motion earthquakes. Knowledge of this degradation process can be used with efficiency in order to assess the time history response and the aseismic design of critical structures such as dams, nuclear power plants and their important facilities.

However the crucial question upon the importance of the nonstationary frequency content remains addressed. Indeed, in order to simplify the random vibration analysis, previous ground motion models have often neglected the temporal variation of the frequency content. Since it is difficult to incorporate this variation in ground motion models, it is believed that it had no significant effect on structural response. Recently, several studies have shown the latter statement to be incorrect and that the nonstationarity in frequency content of the ground motion can have significant effect on nonlinear structural response (Conte, 1992; Papadimiriou, 1992; Aknouche, 1999).

The objective of this study is to identify the effects of the frequency nonstationarity, on the nonlinear structural response, by using a nonstationary stochastic model based on the concept of physical spectrum developed by (Mark, 1986) and simple inelastic structural models.

The nonstationary stochastic model is used to simulate, two sets of artificial earthquakes compatible with a real ground acceleration record and exhibiting similar phases distribution (Tiliouine and al, 2000) and different frequency contents : the first group presents a time varying frequency content and the second one group has a time invariant frequency content.

Three hysteretic models have been considered, (i) Elasto-plastic model (bilinear), (ii) Clough's stiffness degrading model and (iii) Maximum point-oriented bilinear model, the three models are with no strain-hardening. The variability of the maximum displacement ductility was represented in terms of probabilistic inelastic response spectra for the two groups of the precedent simulated accelerograms.

2. THE PHYSICAL SPECTRUM

If we consider the acceleration component $x(t)$, its physical spectrum is defined as

$$P_{XX}(f,t) = \left| \int_{-\infty}^{+\infty} w(t-s)x(s)e^{-j2\pi \cdot fs} ds \right|^2 \tag{2.1}$$

$$P_{XX}(f,t) = \left| \int_{-\infty}^{+\infty} w(t-s)x(s)e^{-j2\pi \cdot fs} ds \right|^2 \tag{2.2}$$

$$P_{XX}(f,t) = \left| \int_{-\infty}^{+\infty} w(t-s)x(s)e^{-j2\pi \cdot fs} ds \right|^2 \tag{2.3}$$

Where f and t represent the frequency and time variables and s a dummy variable. $w(t)$ is a running time window, its functional form is.

$$w(t) = 2\sigma\sqrt{2\pi} e^{\left[-(2\pi\sigma \cdot t)^2\right]} \tag{2.4}$$

The controlling parameter σ is related to the deviation D (half distance between inflexion points) as.

$$D = \frac{\sqrt{2}}{4\pi\sigma} \tag{2.5}$$

With $N = 128$ and $t = 0.02$ sec for filtered accelerogram band-width of 0.07-25 Hz.

3. THE EVOLUTIONARY SPECTRUM MODEL

The model selected to describe the frequency content is of Gaussian shape, and is expressed as follows.

$$S(f,t) = \frac{\alpha(t)}{\sqrt{2\pi} f^s(t)} \exp[-0.5\,(\frac{f - f^0(t)}{f^s(t)})^2] \tag{3.1}$$

Where $f^0(t)$, $f^s(t)$ are the time varying parameters, defined with the use of the so-called spectral moments, named respectively the centroîd and the dispersion of the energy centred on the centroid of the spectrum at the time t. The parameter $\alpha(t)$ is the ratio which ensures the recovery of the original energy under the Gaussian curve at each time instant. Indeed, if we consider the evolutionary spectrum $P_{xx}(f,t)$ of $x(t)$, then $\alpha(t)$ value is computed as

$$\alpha(t) = \sqrt{2\pi} f^{s}(t)\left\{\int_{-\infty}^{+\infty} P_{XX}(f,t)df \Big/ \int_{-\infty}^{+\infty} \exp[-0.5\left(\frac{f - f^{0}(t)}{f^{s}(t)}\right)^{2}]df\right\} \tag{3.2}$$

Figures 1 shows respetively the time evolution of the frequency content of Loma Prieta accelerogram, the time variations of the spectral parameters $f^{0}(t)$, $f^{S}(t)$ and $\alpha(t)$ associated with evolutionary spectrum.

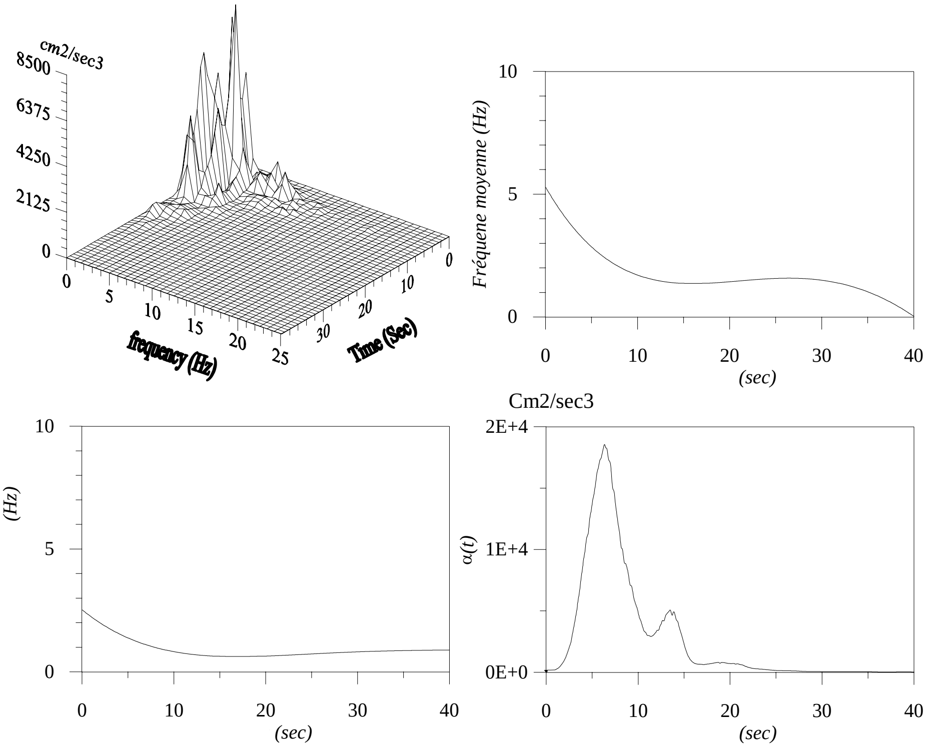

Figure 1 Characterization in the frequency domain of the Loma prieta earthquake record

4. PHASE DISTRIBUTION

The phase generation technique corresponds to the phase derivative probabilistic distribution law which has been introduced by Nigam. This distribution depends on the ratios of the so-called “three intensity moments” associated to the gross properties of the ground acceleration intensity envelope and is given by.

$$P[\phi'(f)] = \frac{t_d^2}{2\left[(\phi'(f) + t_m)^2 + t_d^2\right]^{3/2}} \quad \text{if} \quad \phi'(f) < 0 \tag{4.1}$$

$$P[\phi'(f)] = \frac{t_d^2}{2\left[(\phi'(f) - t_m)^2 + t_d^2\right]^{3/2}} \quad \text{if} \quad \phi'(f) \geq 0 \tag{4.2}$$

Where $\phi'(f)$ denotes the phase derivative with respect to frequency, whereas, t_m and t_d represent, respectively, the “mean” and the “standard deviation” of the intensity envelope function.

Figures 2a to 2d show, respectively, for the horizontal component of the October 17th 1989 Loma Prieta earthquake, the temporal envelope variations, the values phase derivative and the associated phase derivative probabilistic distribution function. It has been noted that the phase derivative distribution for a recorded earthquake ground motion is highly correlated to its envelope shape.

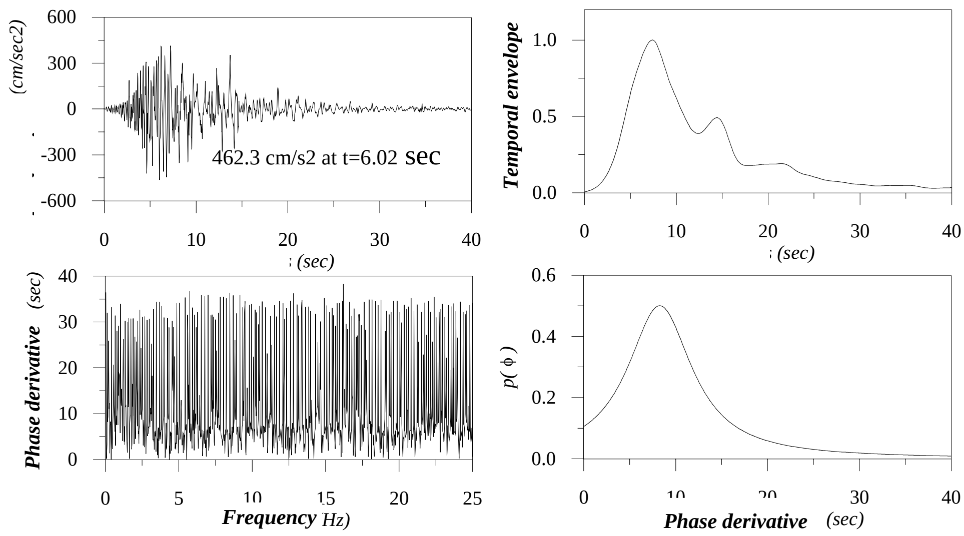

Figure 2 Characterization in time domain of the Loma Prieta record.

5. GROUND MOTION MODELS

The ground acceleration record selected for this investigation is the horizontal component of the October 17, 1989 Loma Prieta earthquake. This accelerogram, characterised by a long period of strong motion, a large peak ground acceleration (PGA) and strong non-stationarities both in amplitude and frequency content, is used as the target record for application of the above-mentioned time invariant and time variant earthquake ground motion models.

To isolate the effects of the frequency nonstationarity of earthquake ground motions on inelastic structural response, it is necessary to introduce a second earthquake model which has the same nonstationarity in amplitude as the first one defined above, but with a time-invariant frequency content. The frequency content of this model is represented by the Fourier amplitude spectrum of the target record. It should be noted that this spectrum can be defined in an equivalent way as a limiting case of the physical spectrum. The constant mean frequency of the second model corresponds to the natural frequency associated with the centroïd of the area under the Fourier amplitude spectrum curve. In the stationary case, the constant mean frequency and the dispersion values associated with the Fourier amplitude spectrum for the Loma Prieta record are set equal to 2.95 Hz and 1.2 Hz respectively.

For the sake of brevity, in the sequel, the earthquake ground motion models with time invariant and time varying frequency content will be referred to as the TIF and TVF models, respectively. It follows that two distinct simulation models of earthquake ground accelerations can be defined.

In figure 3, the curves in dashed lines represent the smoothed normalized instantaneous spectrum for the TVF earthquake model and the curve in solid line represents the smoothed normalized Fourier amplitude spectra for TIF model. It is noticed that the predominant frequencies of recorded ground motion shift to lower frequencies with increasing time, as reflected by the normalized spectrum for the TVF model. This is often observed in earthquake ground motions.

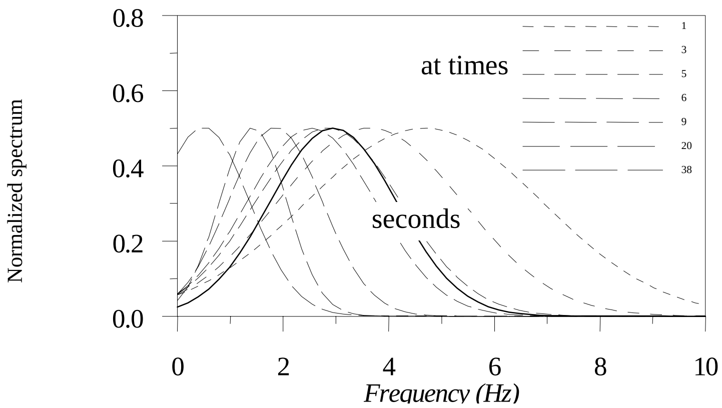

Figure 3 The normalized instantaneous spectrum computed by the TVF (dashed curves) and the TIF (solid curve) models for the accelerogram

6. MODELS OF STRUCTURES BEHAVIOUR

In order to identify the effects of the frequency content model of earthquake ground motion on the seismic response of inelastic structures, single degree of freedom systems with idealised hysteretic behaviour have been used. In this paper, three idealised hysteretic models without strain-hardening illustrated in figure 4 have been considered.

(i) Elasto-plastic model: this model is the elastic-perfect plastic hysteretic model. It can be applied to steel frame structures with large deformation capacities.

(ii) Maximum point-oriented bilinear model: this model is an extreme case that represents such brittle failure as the shear failure short reinforced concrete columns and brick structures.

(iii) Clough's stiffness degrading model: this model is often used when analysing reinforced concrete structures that are expected to fail in flexure.

Notice that these three restoring force models are characterised by the same bilinear skeleton curve, and the corresponding non-linear dynamic single degree of freedom systems are uniquely defined by **(i)** the initial value of period $T_{0,}$ **(ii)** the initial damping ratio $\xi_0 = c/[2(k_0/m)^{1/2}]$ where c and m represent respectively the constant damping coefficient and mass of the system and **(iii)** the strength coefficient $\beta = R_y/m\,g$ expressing the yield strength $R_y = k_0\, m$ of the system as a fraction of its own weight. The elastic limit force is set equal to the double of the horizontal seismic force recommended by the Algerian aseismic code. A direct step by step integration of the damped non linear equation of motion based on Newmark's algorithm with α=1/6 and δ has been used.

For the sake of brevity, the following notations will be used to indicate the various models.

EPP: Perfect elasto-plastic model.
EPO: Maximum point-oriented bilinear model.
PEN: Clough's stiffness degrading model.

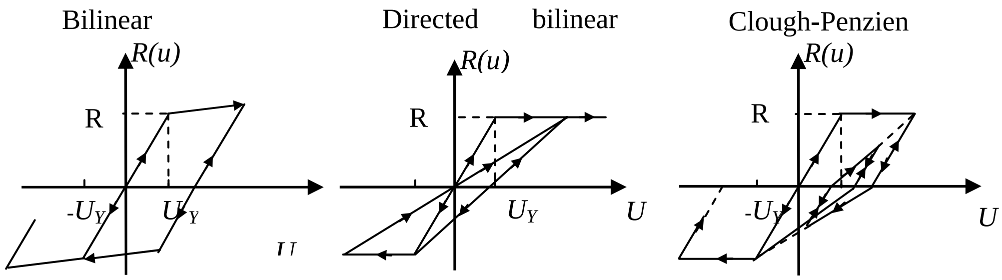

Figure 4 Inelastic behaviour Models

7. ANALYSE AND RESULTS

The ground acceleration record selected for this preliminary investigation is the horizontal component of the October 17, 1989 Loma Prieta earthquake. This accelerogram, characterised by a long period of strong motion, a large peak ground acceleration (PGA) and strong non-stationarities both in amplitude and frequency content, is used as the target record for application of the above-mentioned time invariant and time variant earthquake ground motion models.

The stationary frequency content of the TIF models is represented by the Fourier amplitude spectrum of the target record. It should be noted that this spectrum can be defined in an equivalent way as a limiting case of the physical spectrum. The constant mean frequency of the TIF model corresponds to the natural frequency associated with the centroïd of the area under the Fourier amplitude spectrum curve. The instantaneous frequency of the TVF model at a given time t_k, corresponds to the frequency associated with the centroïd of the area under the instantaneous spectrum curve.

The variability of the structural response parameters was represented in terms of probabilistic inelastic response spectra estimated using the fractile method of order statistics, i.e., the 5, 10, 30, 50, 70, 90 and 95 percentile values of the random response variables are estimated by the 5th, 10th, 30th, 50th, 70th, 90th and 95th largest response values out of the 100 simulated response values (Conte, 1992).

In figures 5, the curves in solid line represent the deterministic ductility response spectra for the three structure models considered and corresponding to the target earthquake whereas the curves in dashed line represent the probabilistic maximum displacement ductility spectra corresponding to the TVF and TIF earthquake and the specified structural model.

From performed critical analysis based on the obtained results, it is found, for the three hysteretic models that the earthquake TVF model produces the largest maximum displacement ductility, for initially stiff structures (T_0<0.3sec). The difference observed between the two sets of simulated accelerograms can be explained by moving resonance phenomena observed by (Conte, 1992; Papadimiriou 1992; Aknouche, 1999).

The amplitude of the effect of this “moving resonance” phenomenon, upon the ground motion duration, depends on the time evolution of the distance between the effective structural frequency and the ground motion instantaneous mean frequency (Conte, 1992; Papadimiriou 1992; Aknouche, 1999), this distance is smaller in the case of TVF model than in that of TIF model. The moving resonance phenomenon is likely to occur for the TIF model. In the present study, the effects of the TVF model, on the maximum displacement ductility response corresponds to a response increase of up to 30 percent.

Figure 5 show a good overall fit between the probabilistic ductility spectra of the target record and the synthetic accelerograms which account for the time varying frequency content of the earthquake (Conte, 1992).

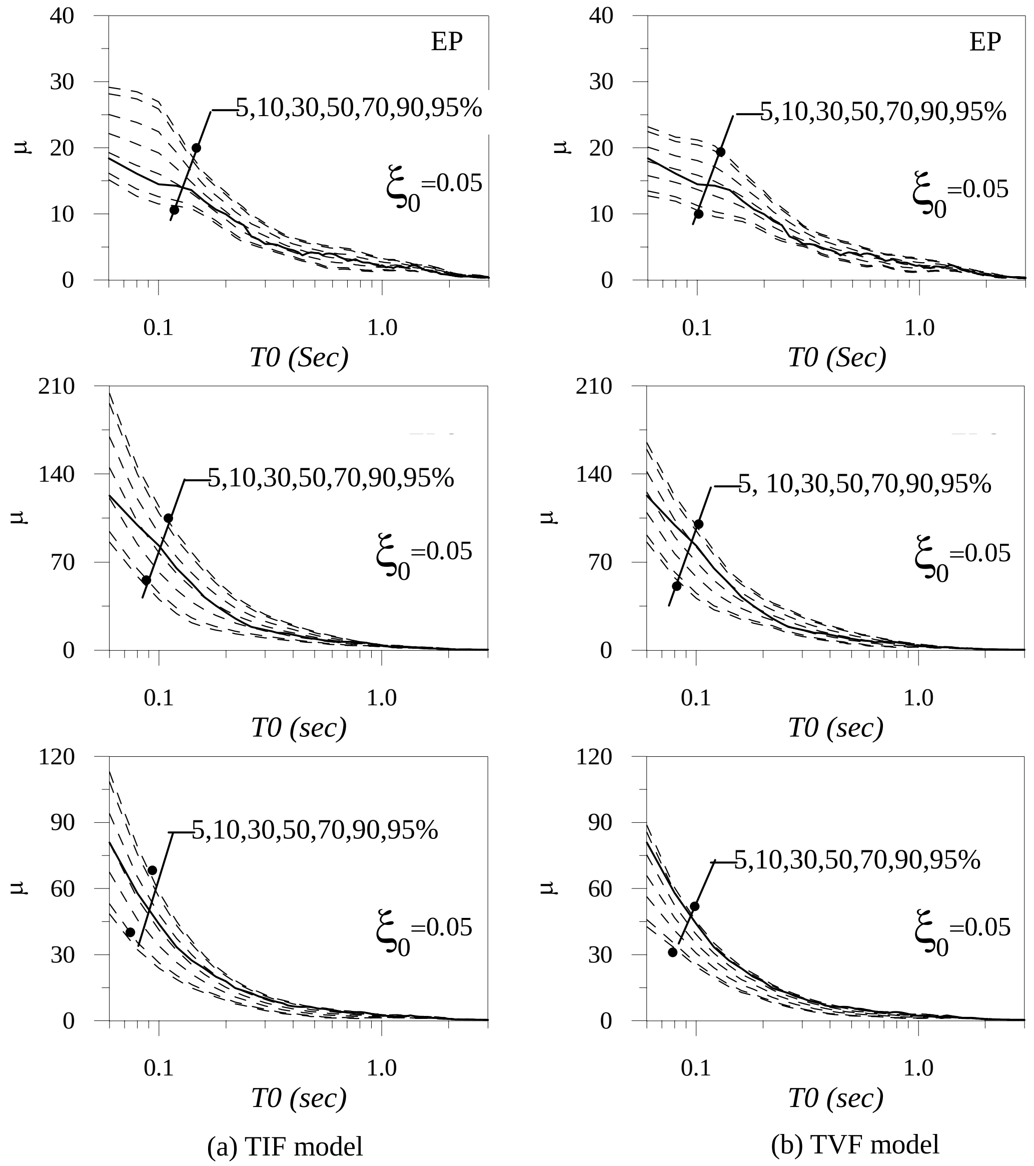

Figure 5 Probabilistic maximum displacement ductility spectra (dashed lines) corresponding to the earthquakes TIF, TVF models and target ductility spectra (solid lines)

8. CONCLUSIONS

The influence of frequency content of earthquake ground motions on inelastic structural response has been examined using TIF and TVF earthquake models based on the concept of physical spectrum. In a preliminary investigation, critical analysis of the obtained results from simulation show that the nonstationarity due to the time variations of the frequency content of the ground motion has a substantial effect for initially stiff structures and can be explained by the ″moving resonance″.

As a conclusion, the characteristics of inelastic structural response depend strongly on the time variation of the frequency content of the excitation. A bad estimate of the spectral contents way leads to levels of amplitudes of the response which are less significant than those be produced by the real response.

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