Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Effects of earthquake frequency nonstationarity on inelastic structural response

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ABSTRACT: This paper presents preliminary results of a study aimed at identifying the effects of the time-varying frequency content of earthquake ground motions on inelastic structural response. Autoregressive - moving average (ARMA) stochastic processes with both time-varying and time-invariant parameters are statistically calibrated against an actual earthquake ground acceleration record. These stochastic earthquake ground motion models are then used to simulate the seismic response of simple inelastic structural models. The variability of various inelastic structural response parameters is represented in terms of probabilistic inelastic response spectra.

1 INTRODUCTION

Earthquake ground acceleration records exhibit nonstationarity in both amplitude and frequency content. The amplitude nonstationarity is typically characterized by the initial build-up of the ground acceleration after the arrival of the first seismic waves, a period of strong motion at more or less constant amplitude, and a final gradual decay. The nonstationarity in frequency content is defined by a change in time of the frequency content of the ground acceleration, i.e., the relative amplitudes of the various frequency components of the ground acceleration change with time. Typically, the frequency content tends to shift towards lower frequencies as time elapses, due to seismic wave dispersion, i.e., The P-waves, S-waves, and surface-waves travel at different speeds and reach a given site at different times.

To account for the inherent uncertainty characterizing earthquake ground motion time histories, the paradigm of viewing an actual earthquake ground motion as a single realization of an underlying stochastic earthquake process is used. Although stochastic earthquake models have been widely accepted in the engineering community, many of them are not able to capture satisfactorily all the key features of actual seismic records influencing structural response. Namely, most existing earthquake models have neglected the frequency nonstationarity for mathematical convenience in random vibration analysis and because it was believed that it had no significant effect on structural response. Recently, several studies have shown the latter belief to be incorrect and that the nonstationarity in frequency content of the ground motion can have significant effect on the response of both linear and nonlinear structures (Saragoni 1972, Yeh & Wen 1990, Papadimitriou 1990). The objective of the study reported here is to investigate systematically the effects of the frequency nonstationarity on structural response by using a stochastic nonstationary ground motion model and simple inelastic structural models.

2 STOCHASTIC EARTHQUAKE GROUND MOTION MODELING

In this study, the inherent randomness characterizing actual earthquake ground motion time histories is modeled using a time-varying autoregressive - moving average stochastic process of order {p,q}, abbreviated ARMA(p,q) model. ARMA models are explicitly formulated in discrete time, which is also the format of earthquake ground motion records (digitized and digital records), and are defined by the following stochastic linear difference equation:

$$a_k - \phi_{1,k} a_{k-1} - \dots - \phi_{p,k} a_{k-p} = e_k - \theta_{1,k} e_{k-1} - \theta_{q,k} e_{k-q} \quad (1)$$

In equation (1), $\{a_k = a(k\,\Delta t)\}$ represents the discrete earthquake ground acceleration process, Δt the sampling time interval, $\{e_k\}$ the driving uncorrelated Gaussian white-noise with variance $\sigma^2_{e,k}$, $(\phi_{i,k}, i=1,...,p)$ and $(\theta_{i,k}, i=1,...,q)$ the time-varying autoregressive and moving average coefficients, respectively. This ARMA stochastic model is able to reproduce the nonstationarity in both amplitude and frequency content characterizing real earthquake records. The nonstationarity in amplitude is modeled by the variance envelope $\sigma^2_{e,k}$ of the driving noise $\{e_k\}$, whereas the nonstationarity in frequency content is represented by the time-varying ARMA filter coefficients.

For a given real earthquake accelerogram, called "target record" and for a specified model order {p,q}, the ARMA model parameters are estimated using an iterative Kalman filtering procedure (Conte et al. 1990).

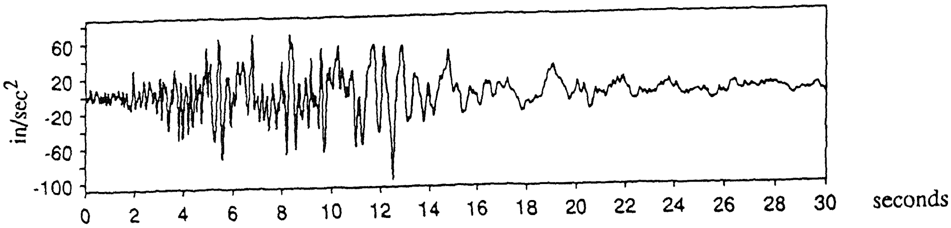

Figure 1 Orion Blvd. earthquake record (comp. N00W) from the San Fernando earthquake of February 9, 1971

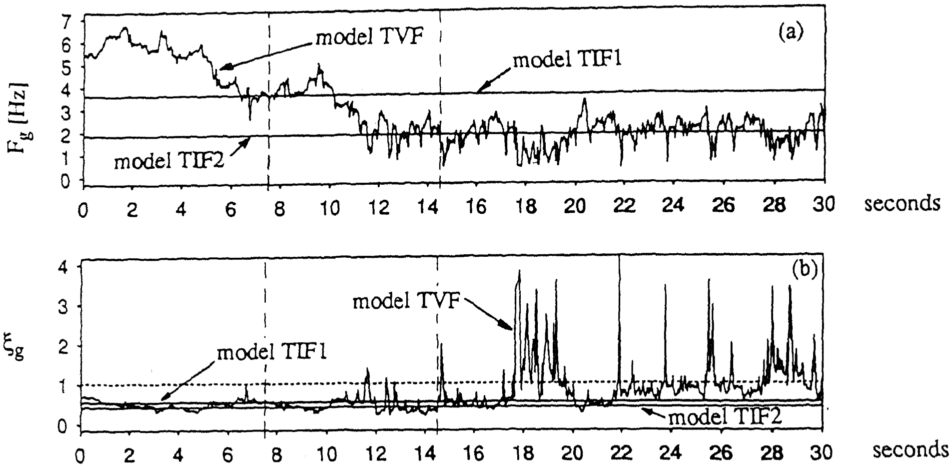

Figure 2 Time histories of physical parameters corresponding to the identified time-varying ARMA(2,1) model

This time-adaptive procedure requires a state-space formulation of the ARMA model and updates in an optimum way the system parameters at each time step using the prediction and the observation of the ground acceleration at each discrete time. The Kalman filtering is iterative because the true noise terms $\{e_k, ..., e_{k-q}\}$ used to explain the ground acceleration value a_k (see equation (1)) are not measured and their variance $\sigma^2_{e,k}$ is needed in the parameter estimation procedure. At each iteration of the estimation scheme, the residuals corresponding to the difference between prediction and observation are used as estimates of the true noise terms from which an estimate of the variance envelope of the driving noise, $\hat{\sigma}^2_{e,k}$, can be obtained. The latter estimate is obtained using a non-parametric envelope estimation technique called the "two-stage weighted moving average estimate" based on averaging over a sliding time-window (Conte et al. 1990). Experience has shown that convergence of $\hat{\sigma}^2_{e,k}$ is generally obtained after a few iterations (e.g. less than 5). Model validation tests are performed on the final (converged) sequence of normalized residuals $\{\hat{e}_k/\hat{\sigma}_{e,k}\}$ generated by the model estimation procedure. If the estimated ARMA model were to fit perfectly the target record, it would map the highly correlated time series of the target record into a realization of a perfectly uncorrelated stationary Gaussian white-noise. Therefore, the residuals of the estimated model are checked for "whiteness" or uncorrelation and normality. If the model is rejected based on these statistical tests, either the estimation procedure is repeated with different "tuning" parameters, or the order $\{p,q\}$ of the ARMA model is changed (increased) and the estimation procedure repeated.

2.1 Stationary versus nonstationary modeling of frequency content

After validation, the estimated ARMA model is used to simulate artificial earthquake ground motions exhibiting similar characteristics in amplitude and frequency content as the target record. 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 model defined above, but a time-invariant frequency content. The fixed frequency content corresponds to some instantaneous frequency content of the fully nonstationary model during the strong phase of ground shaking. For the sake of brevity, in the sequel the earthquake models with Time-Varying Frequency con-

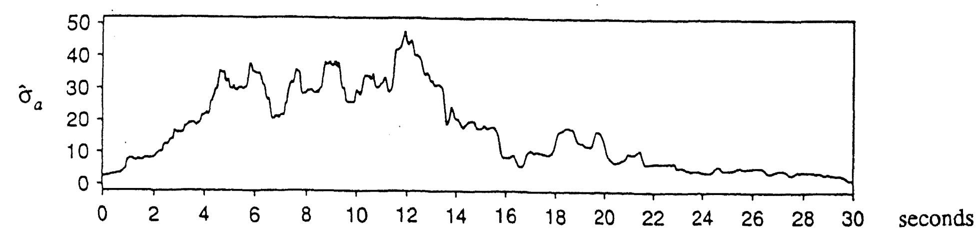

Figure 3 Variance envelope estimate of the Orion Blvd. earthquake record

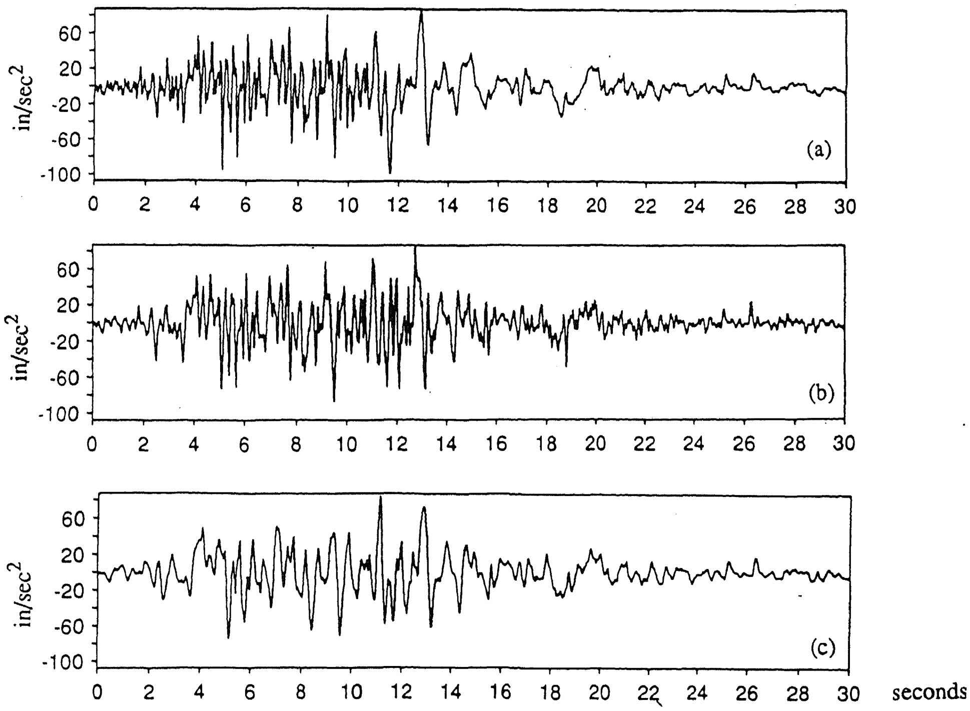

Figure 4 Artificial ground accelerations generated from (a) earthquake model TVF, and (b) earthquake model TIF1
Artificial ground acceleration generated from (c) earthquake model TIF2

tent and Time-Invariant Frequency content will be referred to as the TVF and TIF models, respectively. The artificial earthquake simulation procedure consists of the following: (1) computer generation of a stationary, Gaussian, discrete white-noise; (2) ARMA filtering using the estimated ARMA parameter time-histories $(\hat{\phi}_i(t), i = 1, \ldots, p)$ and $(\hat{\theta}_i(t), i = 1, \ldots, q)$ for the TVF model or a selected fixed set of ARMA parameters for the TIF models; (3) estimation of the variance envelope of the filtered white-noise obtained under (2) using the "two-stage weighted moving average" technique and amplitude-demodulation of the filtered white-noise by scaling it with the inverse of its standard-deviation envelope estimate; (4) amplitude-modulation of the normalized filtered white-noise obtained under (3) using the standard-deviation envelope estimate of the target accelerogram; (4) baseline correction using a high-pass Butterworth filter with cut-off frequency at 0.10 Hz. Uncorrelation between the members of an ensemble of artificial earthquake records simulated from the same estimated earthquake model is insured by using a different seed number for each white-noise sequence generation.

3 CASE STUDY

The Orion Blvd. earthquake record (comp. N00W) from the San Fernando earthquake of February 9, 1971 has been used as the target record for application of the

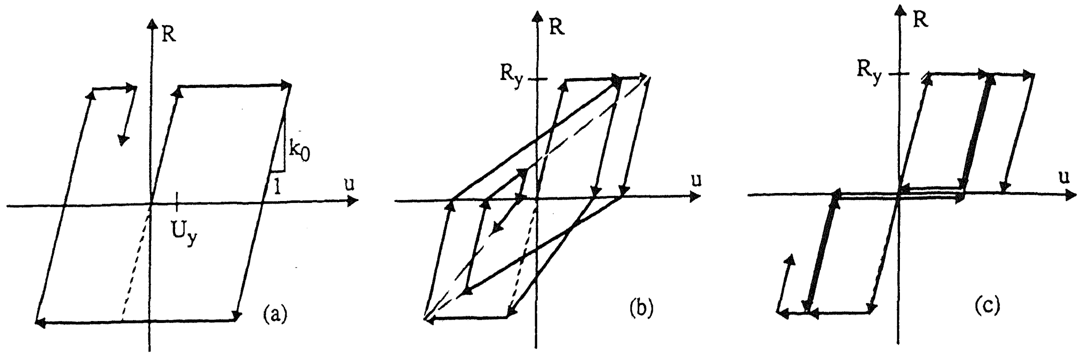

Figure 5 Idealized hysteretic models considered: (a) bilinear model, (b) Clough's stiffness degrading model, and (c) slip model, without strain hardening

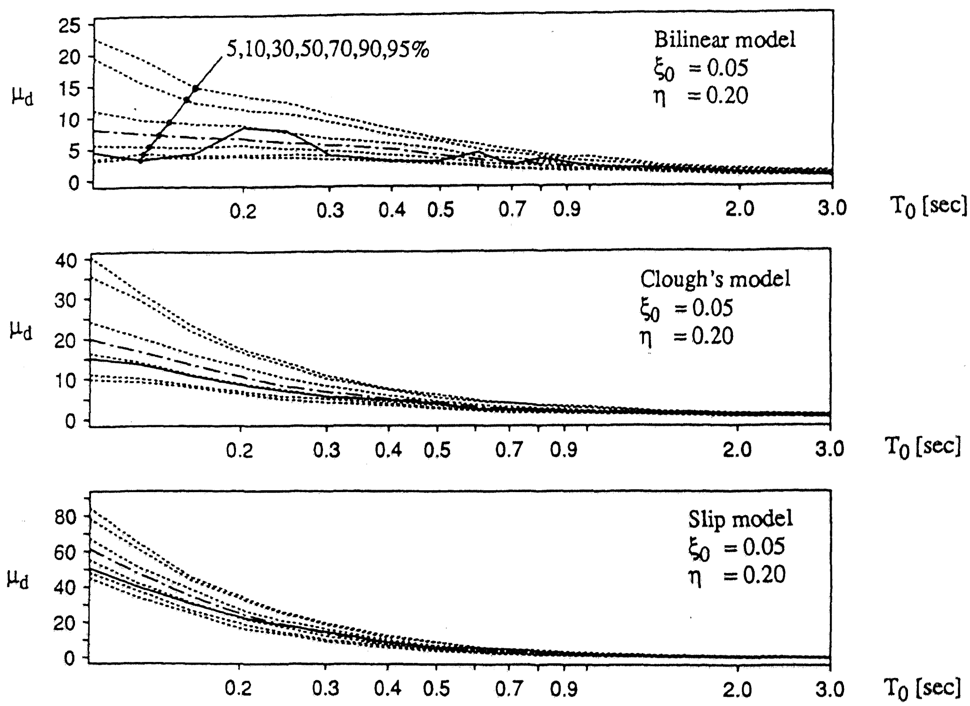

Figure 6 Probabilistic maximum displacement ductility spectra (dashed lines) corresponding to the earthquake model TVF and deterministic target ductility spectra (solid lines)

ARMA modeling described above. As shown in Figure 1, this target record is characterized by a well-pronounced frequency nonstationarity. A time-varying ARMA(2,1) model has been estimated using the iterative Kalman filtering procedure. It can be shown (Conte et al. 1990) that the ARMA(2,1) discrete process is covariance equivalent (discretely coincident) with the continuous response process of a single-degree-of-freedom (SDOF) system excited by a continuous white-noise support acceleration applied separately to the spring and to the dashpot supports in proportion C_s and C_d, respectively. Therefore, once estimated the ARMA(2,1) parameters (ϕ_1, ϕ_2, θ_1) can be mapped into the physical parameters (F_g, ξ_g, C_s/C_d) where F_g and ξ_g stand for the natural frequency and damping ration of the equivalent SDOF oscillator. The parameters F_g and ξ_g can be interpreted as the predominant frequency and the frequency bandwidth of the ground acceleration and are represented in Figure 2 for the case of the Orion Blvd. record. Figure 3 displays the variance envelope estimate of the target record obtained using a sliding time-window of 1.00 second duration (i.e. 51 ground

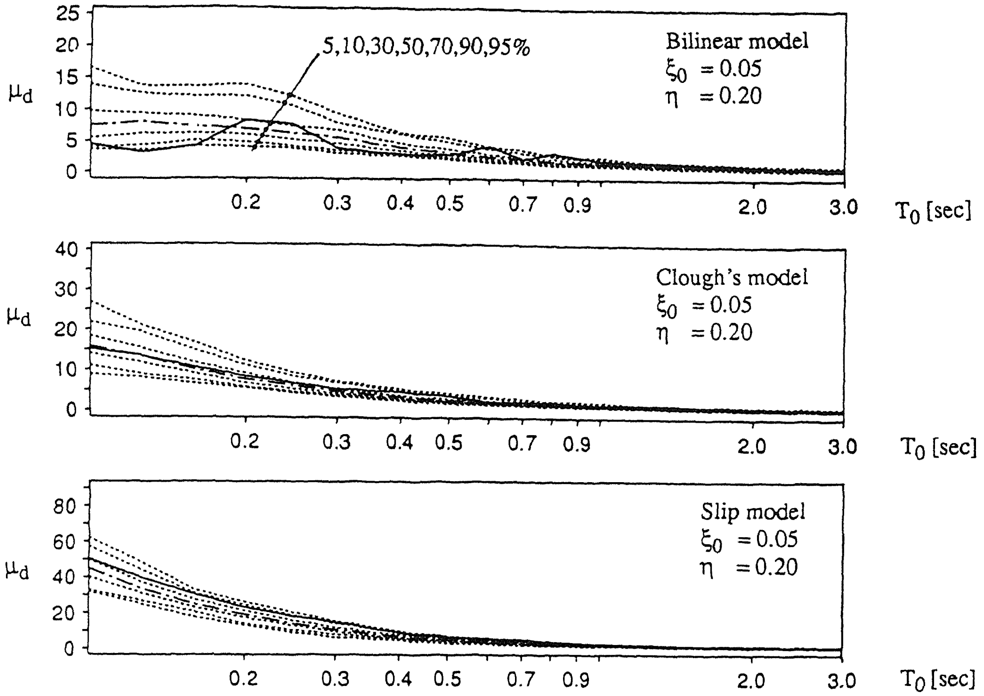

Figure 7 Probabilistic maximum displacement ductility spectra (dashed lines) corresponding to the earthquake model TIF1 and deterministic target ductility spectra (solid lines)

acceleration values). This envelope estimate was used to modulate the amplitude of all artificial earthquake records simulated.

Two earthquake models were defined from the estimated TVF model. These two models, denoted TIF1 and TIF2, correspond to the instantaneous frequency content of the TVF model at times t=7.50 sec and t=14.50 sec, respectively (see Figure 2). It is noticed that the model TIF1 corresponds to a significantly higher frequency content than the model TIF2. Three artificial earthquake accelerograms generated from the earthquake models TVF, TIF1, and TIF2 and corresponding to the same discrete white-noise sequence are plotted in Figures 4(a), (b), and (c), respectively.

To simulate the earthquake response of inelastic structures, SDOF systems with idealized hysteretic behavior have been utilized. The three idealized hysteretic models shown in Figure 5 have been considered, namely (a) the bilinear nondegrading inelastic model, (b) Clough's stiffness degrading model, and (c) the slip model, all three without strain-hardening. Notice that these three restoring force models are characterized by the same bilinear skeleton curve, and the corresponding nonlinear dynamic SDOF systems are uniquely defined by the following structural parameters: (1) the initial natural period T_0, (2) the initial damping ratio $\xi_0 = c/2(k_0 m)^{1/2}$ where c is the constant damping coefficient of the system and m the mass of the system, and (3) the strength coefficient η expressing the yield strength of the system as a fraction of its own weight.

Various structural response parameters were used to characterize the structural response processes, such as maximum displacement ductility μ_d (= maximum relative displacement response u_{max} normalized by the structure yield displacement U_y), cumulative displacement ductility, number and relative amplitudes of yield excursions, maximum or cumulative normalized energy responses (kinetic, viscous damping, and hysteretic energy), and peak rate of energy responses (i.e., maximum power responses).

Three ensembles of 100 artificial earthquake accelerograms were generated using the models TVF, TIF1, and TIF2. For a given set of structural parameters and for each hysteretic model, the corresponding ensembles of response time histories were obtained by deterministic, exact piecewise integration of the equation of motion. The corresponding ensembles of structural response parameters were computed and analyzed statistically. The variability of the structural response parameters was represented in terms of probabilistic inelastic response spectra (or damage 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. For example, Figures 6, 7, and 8 represent the probabilistic maximum displacement ductility spectra (dashed lines) for the three structural models considered and corresponding

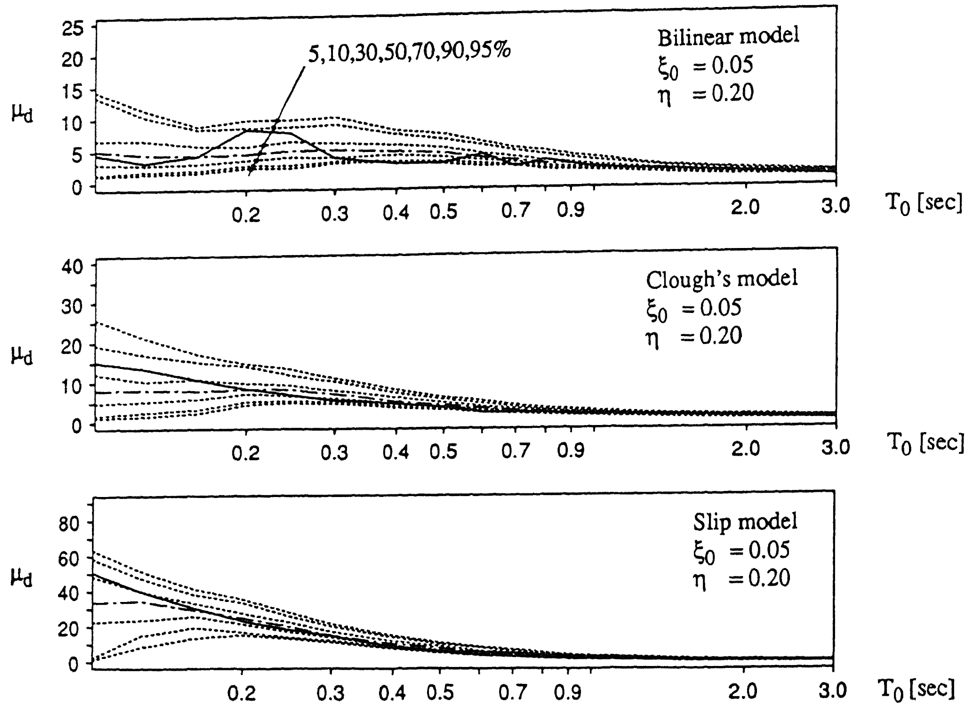

Figure 8 Probabilistic maximum displacement ductility spectra (dashed lines) corresponding to the earthquake model TIF2 and deterministic target ductility spectra (solid lines)

to the earthquake models TVF, TIF1, and TIF2, respectively. In these same figures, the curves in solid line represent the deterministic ductility response spectra corresponding to the target earthquake and the specified structural model.

DISCUSSION OF RESULTS

By examining Figures 6, 7, and 8, it is found that a better overall fit over the range of structural periods between the probabilistic ductility spectra and the corresponding target deterministic spectra is realized for the earthquake model TVF which accounts for the time-varying frequency content of the earthquake. It is also found that for a given probability of exceedence and for initially stiff structures ($T_0 < 0.30$ sec), the earthquake model TVF produces the largest maximum displacement ductility μ_d for all three hysteretic models. This can be explained by the "moving resonance" effect observed by Papadimitriou (1990) for softening elastic systems and earlier by Saragoni (1972) for degrading hysteretic systems. The increasing "effective period" of vibration of an inelastic structure as yielding occurs tracks the decreasing predominant frequency of the ground motion. The amplitude of the effects of this "moving resonance" phenomenon depends on the "distance" between the effective structural frequency and the ground predominant frequency and the time-evolution of this "distance". In the present case study, for initially stiff structures, the effects of the time-varying frequency content, which can be explained by the "moving resonance" effect, on the maximum displacement ductility response corresponds to a response increase of up to 60 percent.

4 CONCLUDING REMARKS

The influence of the time-varying frequency content of earthquake ground motions on inelastic structural response has been examined statistically by using a time-varying ARMA stochastic earthquake model able to represent very closely the amplitude and frequency nonstationarity of an actual earthquake accelerogram exhibiting a pronounced frequency nonstationarity. From statistical analysis of simulation results, it was found that this influence can be important and can be explained by the "moving resonance" phenomenon. It is believed that more insight into these frequency nonstationarity effects can be gained from analytical nonlinear random vibration studies involving nonlinear hysteretic systems and realistic, analytical, nonstationary stochastic ground motion models. In the future, these significant effects of the frequency nonstationarity of earthquake ground motions on inelastic structural response should be accounted for in earthquake resistant design.

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