Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.V)

7-5-12

USE OF ARMA MODELS FOR THE INVESTIGATION OF EARTHQUAKE-INDUCED DAMAGE MECHANISMS IN STRUCTURES

Mark A. AUSTIN[1], Joel P. CONTE[2],
Stephen A. MAHIN[3] and Karl S. PISTER[4]

[1]Assistant Professor, Systems Research Center, University of Maryland, College Park, MD 20742, USA
[2]Research Assistant,
[3]Professor of Civil Engineering,
[4]Dean and Roy W. Carlson Professor of Engineering,
University of California, Berkeley, CA 94720, USA

SUMMARY

The design of earthquake resistant structures is often complicated by an inadequate number of suitably recorded ground motions, and by our limited understanding of the basic cause and effect relationships coupling the structural response to the details of a ground motion excitation. The use of ARMA models in design has recently been proposed as a means of mitigating these difficulties. This paper describes preliminary results of an investigation aimed at identifying the key factors affecting the response and behavior of a linear viscously damped SDOF structural model excited by a low order ARMA(2,1) ground motion model.

INTRODUCTION

Although it is possible to design a structure to resist severe lateral earthquake loads elastically, economic factors usually dictate that it is more feasible to design a system having the largest energy dissipation capacity consistent with tolerable deformations. For such a structure to survive these motions without collapse, its members should reach full plastic yielding before maximum lateral displacements are attained. Unfortunately, the problem of enforcing these design requirements is often complicated by the scarcity of suitable recorded ground motions, and the large uncertainty in predicting the spatial and temporal nature of future seismic events. Further uncertainties are introduced due to the limited ability of analytical models to describe nonlinear behavior, and by the high sensitivity of inelastic structural response to the overall intensity, duration and frequency content of earthquake excitations.

Most current design codes (Refs. 1,2) circumvent these difficulties by approaching the conventional design problem indirectly via load and resistance factors, simplified equivalent loads, and elastic analyses. Such approaches to design are inadequate for the design of complex or irregular systems, those composed of a new materials, or ones requiring an enhanced level of post-earthquake functionality. What they require instead, is the formulation and use of design methodologies that explicitly evaluate design performance in a manner consistent with expected design behavior.

Past Work At the University of California, Berkeley, the thrust of the early research in this area focussed on the development of DELIGHT.STRUCT (Refs. 3,4) and a design methodology that includes linear and nonlinear time history analyses, and reliability-based ideas within the design process itself (Refs. 5,6). The essential steps of this statistically-based design method are:

[a] Choose the design parameters, ie: structural system, geometrical configuration, stiffness, strength and mass distribution, etc.

[b] Generate a family of real or artificial ground motion records for each limit state considered, and perform dynamic analyses for each input motion, to explicitly account for the scatter in structural

response outputs due to earthquake loads. A realistic nonlinear mathematical model (e.g., finite element model) of the structure is used for those limit states where extensive inelastic deformations are expected.

[c] Evaluate the design based on criteria expressed in terms of the statistics of key response parameters of the model. Typical quantities are maximum ductility, cumulative plastic deformation, hysteretic energy dissipation, and story drift. The design criteria ensure that the structure behaves according to the accepted design philosophy.

Research Objectives Our preliminary results (Ref. 7) indicate that the reliable reproduction of mean extreme frame response levels and their variations is essential to the effective implementation of the proposed statistical design method. Currently, this goal is difficult to achieve because the basic cause and effect mechanisms existing between the features of a ground motion, the properties of a structure, and the resulting structural damage are poorly understood. Additional complications occur when the number of available ground motions is insufficient. One way of mitigating the latter difficulty is to use Auto-Regressive Moving Average (ARMA) models to generate supplementary families of ground motions that are statistically similar to a real target earthquake. In an effort to work towards a solution of these problems, we have initiated a study to identify the key factors affecting the response and behavior of a linear viscously damped SDOF structural model excited by a low order ARMA(2,1) ground motion model. This paper reports on our preliminary findings.

DESCRIPTION OF THE ARMA MODEL

Discrete ARMA models lend themselves to digital simulation in the time domain and can easily be adapted to include changes in frequency content of earthquake ground motions (EGM's). The ARMA(2,1) model is particularly attractive because of its simplicity, and demonstrated ability to provide a best-fit to many California earthquakes (Refs. 8,9,10). The second order autoregressive - first order moving average difference equation is:

$$a_t - \phi_1 a_{t-1} - \phi_2 a_{t-2} = w_t - \theta_1 w_{t-1} \tag{1}$$

where $\{w_t\}$ represents an input discrete white-noise process and $\{a_t\}$ the output process simulating the digitized ground acceleration process at time t. Considerations of stability and finite energy require that the autoregressive coefficients ϕ_1 and ϕ_2 lie inside the triangular region defined by:

$$\phi_1 + \phi_2 < 1 \quad , \quad \phi_2 - \phi_1 < 1 \quad , \quad |\phi_2| < 1 \tag{2}$$

In addition, the moving average coefficient θ_1 has to satisfy $|\theta_1| < 1$ for the process to be invertible. While the nonstationary intensity of EGM's may be accounted for by multiplying the white noise by a non-negative function $\Psi(t)$, the ARMA parameters may be varied as a function of time to account for the transient frequency content of real ground motions.

An interesting duality exists between the ARMA parameters and the physical parameters of an underlying continuous dynamic system whose stochastic process corresponds to the output from a discrete linear dynamic system driven by white-noise. Indeed, in Ref. 7. it is shown that the autocorrelation functions of the ARMA(2,1) model and SDOF linear oscillator shown in Fig. 1. are discretely coincident when the roots of the characteristic equation:

$$r^2 - \phi_1 r - \phi_2 = 0 \tag{3}$$

are either complex conjugates or both real positive. Whereas the underlying system is underdamped ($\xi_g < 1$) in the former case, it is overdamped ($\xi_g > 1$) when both of the roots are real positive. If at least one root of the characteristic equation is negative, then the corresponding ARMA(2,1) model is not physically realizable, i.e., not discretely coincident with an unique underlying physical system at all discrete time lags ($k\Delta t$, $k = 0, 1, 2, \cdots$).

Moreover, the discrete/continuous model relationships are defined by a (3 x 3) nonlinear one-to-one mapping between the ARMA parameters (ϕ_1, ϕ_2, θ_1) and the physical parameters (T_g , ξ_g , (C_0/C_1)). Figs. 2., 3. and 4. show these relationships in the form of contour maps of the physical parameters T_g, ξ_g , (C_0/C_1) in the autoregressive plane (ϕ_1 , ϕ_2). T_g and ξ_g are independent of θ_1, but C_0/C_1 depends on θ_1 and Fig. 4. corresponds to $\theta_1 = 0$. In ground motion modeling, T_g is the site predominant period, and ξ_g a damping coefficient that governs the spectral bandwidth of the ground motion process. It is interesting to note that the Kanai-Tajimi filter (Ref. 11) widely used for earthquake simulation corresponds to the particular case $C_0/C_1 = 1$.

NUMERICAL SIMULATION

Ensembles of artificial EGM's were systematically generated for ARMA parameters ϕ_1 and ϕ_2 lying on the triangular grid of constant mesh size shown in Fig. 5. For all the simulations the moving-average parameter θ_1 was set to zero, and a time-dependent envelope, $\Psi(t)$, of the form:

$$\Psi(t) = A_0 \, \alpha \left(\frac{t}{\tau} \right)^3 \exp\left[-A_1 \left(\frac{t}{\tau} \right) \right] \tag{4}$$

where $A_0 = \left(\dfrac{8e^3}{3\sqrt{3}} \right)$

$A_1 = 2\sqrt{3}$

t = *time (seconds)*

α = *max amplitude of* $\Psi(t)$

τ = *duration of strong shaking (seconds)*

assumed. At each grid point, families of twenty non cross-correlated EGM's were generated by working through the following sequence of operations: (a) generation of discrete Gaussian white-noise, (b) time modulation and amplitude scaling (c) ARMA filtering, and (d) baseline correction. Although τ was held constant at 5 *seconds* for all the simulations, parameter values for α were automatically adjusted so that the maximum value of the ground motion variance envelope would be constant for all the grid points.

Both ground motion and structural response parameters were evaluated for each simulated input motion. Among the traditional ground motion parameters computed were: peak ground acceleration (PGA), velocity (PGV) and displacement (PGD), Arias intensity, Housner spectral intensity (S.I.). Similarly, the spectra of various response quantities (relative and absolute, real and pseudo, displacement,velocity and acceleration) of the linear SDOF structure were computed using the piece-wise exact method of integration of the differential equation of motion.

The results of interest are the second order statistics (mean and standard deviation) of the ground motions and structural response parameters associated with each family of ARMA generated earthquakes. A sample of these results is presented in Figs. 6-9 for the ground motion parameters, and in Figs. 10-13 for the structural response parameters. These figures indicate (i) evidence of the resonance condition effect for elastic stuctures and (ii) that the coefficient of variation (C.O.V.) of the structural response parameters are almost insensitive to the ARMA parameters and hence to the spectral properties of the input motion.

CONCLUSIONS AND FUTURE WORK

The long term objectives of this research project are to formulate design methodologies and develop computer software that links the components: (a) seismology, (b) earthquake ground motion modeling, and (c) structural response and structural reliability, into a single design process. Ideally, these methodologies should take into account the statistical information available on previous earthquake ground motions at the design site, together with information on the multi-source character of the seismic environment, and the relative probability of occurrence of earthquakes being generated at the various known sources.

However, these goals will not be reached without an improved understanding of the basic interaction mechanisms existing between an earthquake ground motion, the properties of a structure, and the resulting structural response. Although discussion in this paper has been restricted to the statistical response of linear structures to a small class of ARMA generated ground motions, our problem solving approach is in fact quite general. In the immediate future, the thrust of our work will be directed towards the identification of cause and effect relations existing between low order ARMA model ground motions, and their effect on nonlinear hysteretic SDOF structures. Careful attention will be given to the characterization of damage in a statistical setting. Because real earthquakes exhibit considerable variations in both the shape and magnitude of the variance envelope, as well as the frequency content of ground shaking itself, further work is also needed to extend the basic ARMA models used in this study, so that the expected ground shaking at a site is more realistically modeled.

REFERENCES

1. Applied Technology Council, "Working Draft of Recommended Seismic Design Provisions for Buildings," January 1976.

2. Uniform Building Code, International Conference of Building Officials, Whittier, CA, 1979 Edition.

3. Austin M.A., Pister K.S., Mahin S.A., "Probabilistic Limit States Design of Moment-Resistant Frames under Seismic Loading," *Journal of the Structural Division*, ASCE, August 1987.

4. Balling R.J., Ciampi V., and Pister K.S., "Interactive Optimization-Based Design of Seismically Loaded Structures," *Proceedings,* 7th European Conference on Earthquake Engineering, Athens, Greece, September, 1982.

5. Austin M.A., Pister K.S., Mahin S.A., "A Methodology for the Computer-Aided Design of Seismic-Resistant Steel Structures," *Report* No UCB/EERC-85/13, Earthquake Engineering Research Center, University of California, Berkeley, December 1985.

6. Austin M.A., Pister K.S., Mahin S.A., "A Methodology for the Probabilistic Limit States Design of Earthquake-Resistant Structures," *Journal of the Structural Division*, ASCE, August 1987.

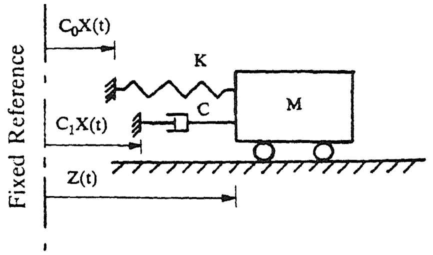
7. Conte J., "ARMA Models for Earthquake Excitation and Structural Response Simulation," *CE299 Report*, Department of Civil Engineering, University of California, Berkeley, 1988.

8. Cakmak A.S., Sherif R.L. and Ellis G., "Modelling Earthquake Ground Motions in California using Parametric Time Series Methods," *Soil Dynamics and Earthquake Engineering*, Vol 4, No 3, 1985.

9. Chang M.K., Kwiakowski J.W., Nau R.F., Oliver R.M. and Pister K.S. "ARMA Models for Earthquake Ground Motions," *Earthquake Engineering and Structural Dynamics*, Vol 10, pp 651-662, 1982.

10. Nau R.F., Oliver R.M. and Pister K.S., "Simulating and analyzing artificial non-stationary earthquake ground motions," *Bulletin of the Seismological Society of America*, Vol. 72, pp 625-636, 1982.

11. Tajimi, H., "A Statistical Method of Determining the Maximum Response of a Building During an Earthquake," *Proceedings*, 2nd World Conference on Earthquake Engineering, Tokyo, 1960.



X(t) : input displacement

$C_0X(t)$: spring support displacement

$C_1X(t)$: dashpot support displacement

Z(t) : SDOF absolute displacement

Fig. 1 Underlying Physical System

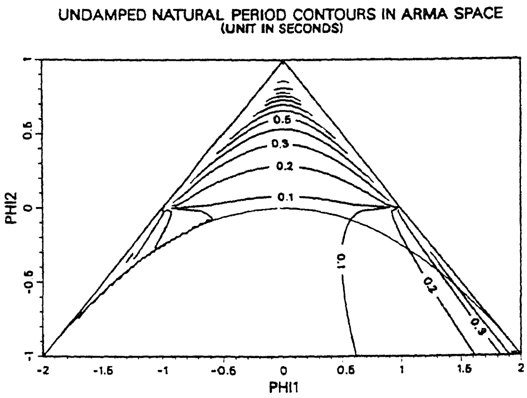


Fig. 2

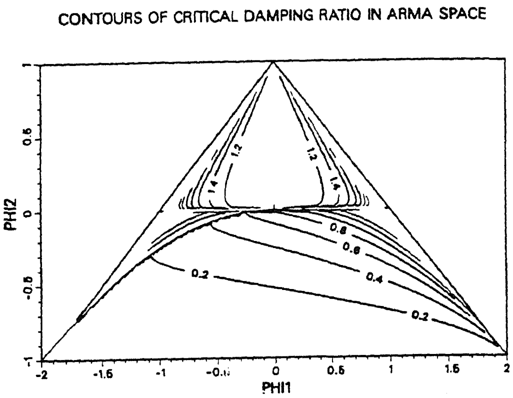


Fig. 3

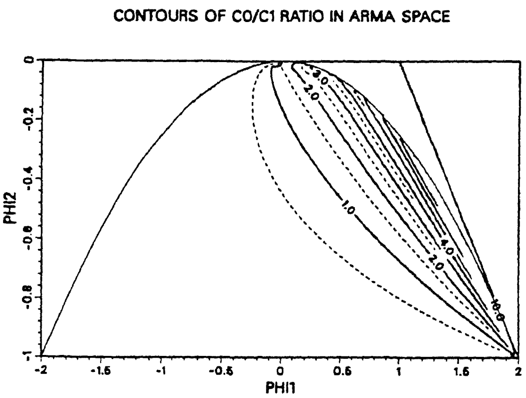


Fig. 4

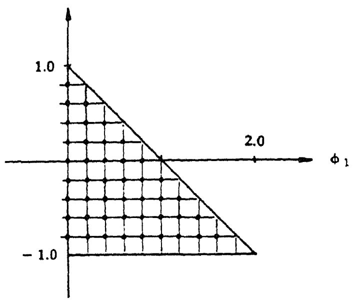


Fig. 5 Grid for Generation of Earthquake Families

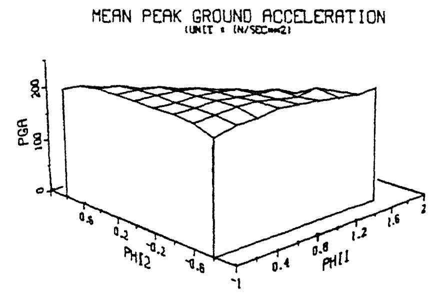


Fig. 6

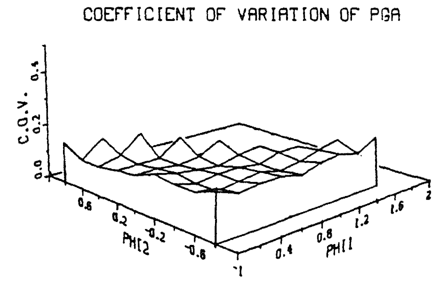


Fig. 7

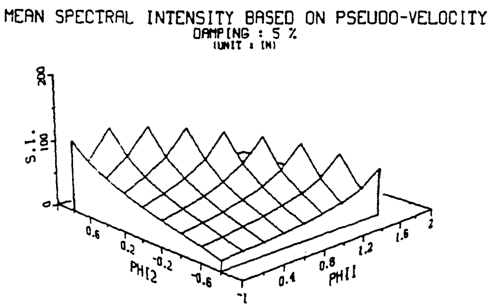


Fig. 8

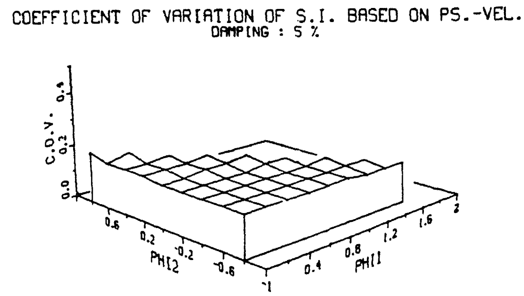


Fig. 9

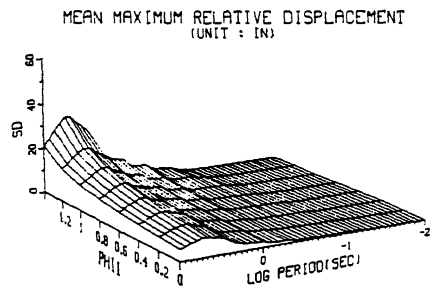


Fig. 10

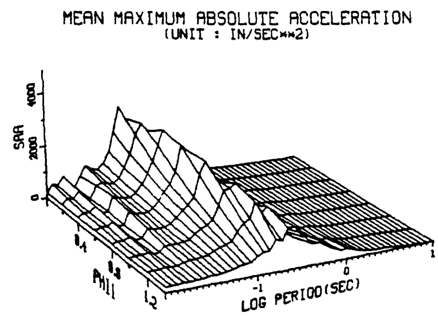


Fig. 11

PHI2 = -0.60
THETA1 = 0.00
DAMPING = 0 %

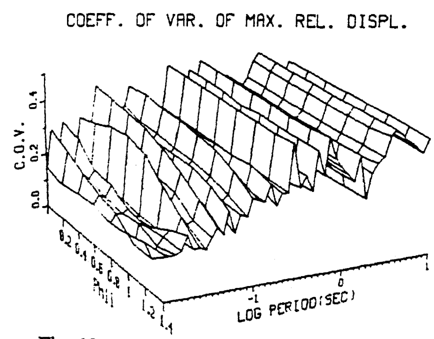


Fig. 13

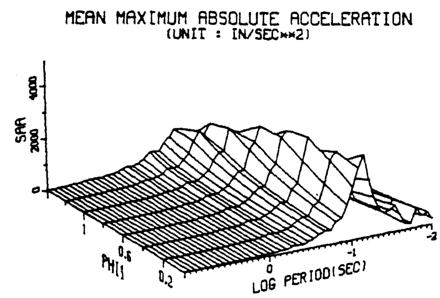


Fig. 12