EARTHQUAKE ENVIRONMENT SIMULATION BY PULSE GENERATORS

by

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SUMMARY

Simple mechanical pulse-generating devices of fairly recent development are capable of producing short duration forces of large magnitudes over a wide frequency range that can be controlled to satisfy multimode system response. This paper is concerned with the simulation of the motion of typical structural systems subjected to earthquake environments by using suitable pulse trains applied at various locations on the structure. The pulses are selected in such a way that the resulting vibration of the structure matches closely the response that would be produced by the earthquake excitation, as determined by an appropriate error criterion. A suitable optimization algorithm is presented and applied to two realistic example structural systems. It is shown that pulse-excitation techniques offer a viable alternative to conventional testing approaches.

INTRODUCTION

The capability for simulating the response of structures to transient dynamic loadings, such as earthquakes and blast loads, is useful for testing structural adequacy, for improving mathematical models, and for investigating the response of equipment in a structure [1]. In addition to various types of vibration generators that are appropriate for certain classes of structural systems, large testing facilities (which have limited availability) and ground-explosion approaches (which are economically prohibitive) can be used for dynamic tests on equipment and structural systems [2,3].

Housner [4] demonstrated the feasibility of using a sequence of discrete pulses with random amplitude to represent the effects of earthquakes on dynamic systems. Scruton and Harding [5] used a crude explosive charge to excite a tall chimney in order to determine its damping characteristics.

A simple mechanical pulse-generating device of fairly recent development [6] is capable of producing short duration forces of large magnitudes over a wide frequency range that can be controlled to satisfy multimode system response. Such force pulse generators have been successfully used to simulate the in-place motions of up to 500 Hz in equipment weighing up to 200,000 lb and in also measuring system impedance functions [7,8].

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This paper is concerned with the simulation of the motion of typical structural systems subjected to earthquake environments, by using suitable pulse trains applied at various locations on the structure. Since a discrete number of pulses superficially presents an appearance quite different from a continuous earthquake ground motion, it becomes necessary to select the pulses on the structure in such a way that the resulting vibration matches as closely as possible the response produced by the earthquake ground motion as determined by an appropriate error criterion.

OPTIMIZATION TECHNIQUE

Statement of the Problem

Note that the method of Fig. 1 requires that the criterion response to the continuous input be known, which would generally not be true in practice. To accomplish this objective, the approach proposed here assumes that: (1) a mathematical model of the system under study is known and (2) the inputs of interest (e.g., earthquake or nuclear blast) are given. Under these conditions, the "criterion response" can be calculated and subsequently used to obtain the pulse trains for the simulated test.

The basic criterion used in this study is the integral squared error between the reference and simulated response, evaluated at a sufficient number of locations within the multiple degree-of-freedom system to characterize it as completely as possible. Given the error criterion, then the pulse occurrence times, pulse widths, and the pulse amplitudes are selected by a systematic search algorithm such that the error is minimized.

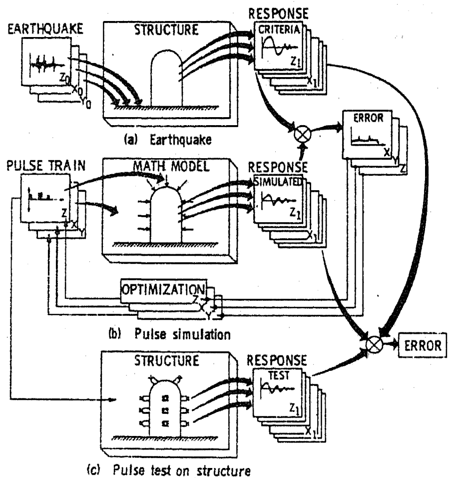


FIGURE 1. PROCEDURE FOR PULSE SIMULATION/ TEST OF A STRUCTURE TO SIMULATE EARTHQUAKE RESPONSE

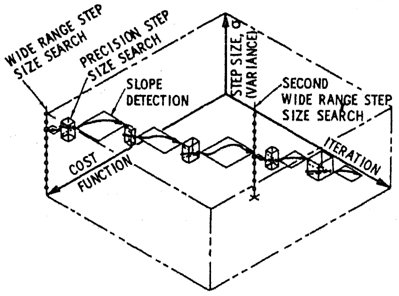


FIGURE 2. ADAPTIVE RANDOM SEARCH, WIDE RANGE AND PRECISION STEP SIZE

Formulation

Consider an n-degree-of-freedom system governed by m nonlinear first-order differential equations of the form

$$\ddot{z}_i = Z\,(z_1, z_2, \ldots, z_m, t), \qquad i = 1,2,\ldots,m \tag{1}$$

where $m = 2n$, and the system is subjected to an excitation force vector $\underset{\sim}{G}(t)$. Let the response of the system to this force (the criterion response) at location i in the structure be denoted $\hat{x}_i(t)$, $i = 1,2,\ldots,k$, where k is the number of locations whose motion is to be monitored.

In order to compare the response of the system model, $\underset{\sim}{x}(t)$, to the criterion response $\hat{\underset{\sim}{x}}(t)$, we select the displacements and velocities at k locations. We now define a nonnegative error criterion

$$J = \int_{t_o}^{t_f} \sum_{i=1}^{k} \left\{ C_{1_i}\left[x_i(t) - \hat{x}_i(t)\right]^2 + C_{2_i}\left[\dot{x}_i(t) - \dot{\hat{x}}_i(t)\right]^2 \right\} dt \tag{2}$$

which measures the "goodness of fit" of the system response variables $\underset{\sim}{x}(t)$ to the specified response $\hat{\underset{\sim}{x}}(t)$. The k constants C_{1_i} and C_{2_i} are weighting factors that can be adjusted to emphasize or de-emphasize the significance of the fit at different points in a structure, since a good fit at some points may be much more important for simulating damage and malfunctions.

The specified or criterion responses $\hat{x}_i(t)$ are those recorded in the structure (as during an earthquake) or obtained from applying known excitation forces to the model of Eq. 1. Since our objective is to find a pulse excitation $\underset{\sim}{F}(t)$ that produces a response $\underset{\sim}{x}(t)$ as close as possible to $\hat{\underset{\sim}{x}}(t)$, we restrict each component of $\underset{\sim}{F}(t)$ to the form

$$F_i(t) = \sum_{j=1}^{N} A_j\left[u(t - t_j) - u(t - t_j - W_j)\right] \tag{3}$$

where

A_j = Amplitude of the jth pulse

W_j = Width of the jth pulse

t_j = Initiation time of the jth pulse

and

$u(t)$ = Unit step function

The problem may now be stated precisely as follows:

Given a system that is described by Eq. 1 and a desired time history vector $\hat{\underset{\sim}{x}}(t)$, find the set of numbers $\{t_j, A_j, W_j\}$, $j = 1,2,\ldots N$, which describes each component of the excitation vector such that the error criterion of Eq. 2 is minimized.

Algorithm

The optimization problem consists of selecting the triplet of numbers (t_j, A_j, W_j), which characterizes each input pulse at various system excitation points. In principle, a large number of optimization procedures for such problems are available [9]. However, in view of the large number of parameters possible in this system, the set of feasible optimization procedures is quite limited. Consequently, an adaptive random search algorithm [10] was selected to determine the optimum parameter values for the pulse trains.

The algorithm for the adaptive random search consists of alternating sequences of a global random search with a fixed value for the step-size variance σ^2 followed by searches for the locally optimal σ^2. Fig. 2 illustrates the adaptive algorithm whereby a very wide-range search selects the best standard deviation of step size σ for the coarseness of the increments used, followed by a sequential precision search of finer increments. As the rate of convergence decreases, a new precision search is made, but is directed toward a smaller step size. At selected iteration intervals, the wide-range search is reintroduced to prevent convergence to local minima. The complete algorithm is described in [10].

APPLICATIONS

The optimization procedure was then applied to two test structures: (1) a typical 25-story building model and (2) a 3-story building frame model that has been extensively tested at the University of California at Berkeley (UCB) shaking table facilities. In each case, the mathematical models of the structures were subjected to a ground motion corresponding to El Centro earthquake record to generate the criteria response. Then for each structure, an appropriate selection of pulse trains was determined in order to minimize the mean-square deviation between the criterion response and the simulated response. The pulse characteristics are, at the same time, constrained to realizable physical values for the test.

Model of 25-Story Building

The system shown in Fig. 3 is a 25-story office building designed in accordance with applicable building code provisions for recommended lateral force requirements [11]. Modal analysis of this building, treated as a linear elastic structure, yields the mode shapes and natural frequencies shown in Fig. 4.

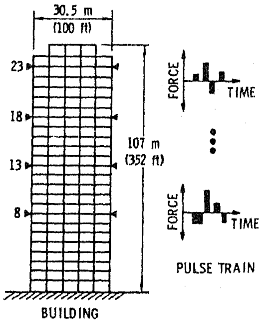


FIGURE 3. GAS PULSERS ARRAYED FOR EARTHQUAKE SIMULATION TEST OF A MULTISTORY BUILDING

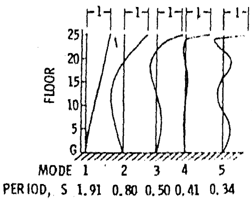


FIGURE 4. BUILDING NATURAL MODES OF VIBRATION

To illustrate the simulation procedure outlined above, it was decided to use four pulse-excitation locations at modal antinodes (Floors 8, 13, 18, and 23) and to attempt to match the response of two locations (Floors 13 and 23). Due to the linearity of the system, its transient response to pulse trains could be determined by using the convolution integral approach. The necessary impulse response functions were determined and are illustrated in Fig. 5 where $h_i^{(j)}(t)$ denotes the response of location i due to a unit impulse applied at location j.

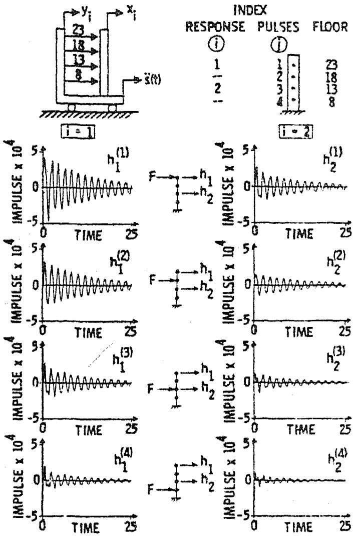


FIGURE 5. IMPULSIVE DISPLACEMENT RESPONSE TO 25 DOF SYSTEM

The El Centro 1940 earthquake ground motion was used as specified base input, and it is resulted in the criteria response shown in Figs. 6a and 6b as solid lines. The earthquake criteria response was simulated by four suitable pulse trains using the optimization algorithim outlined above. The simulated response is superposed on top of the criteria response in Fig. 6, and the time histories of the four required pulse trains are shown in Fig. 7. The ordinates of the response and excitation time histories shown in Figs. 6 and 7 are expressed in terms of dimensionless units.

It is clear from the comparison shown in Fig. 6 that a good match is obtained between the criterion and simulated response. Note that this simulation of the motion over a period of ≈20 sec required ≈13 pulses in each of the four pulse trains.

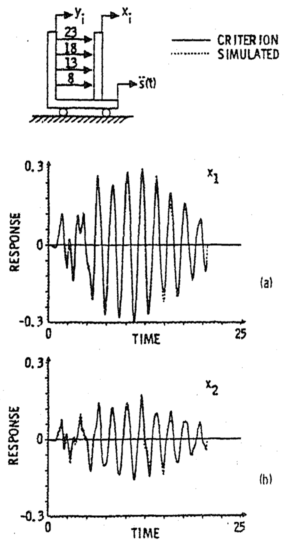


FIGURE 6. COMPARISON OF CRITERION AND SIMULATED RESPONSE OF 25 DOF SYSTEM

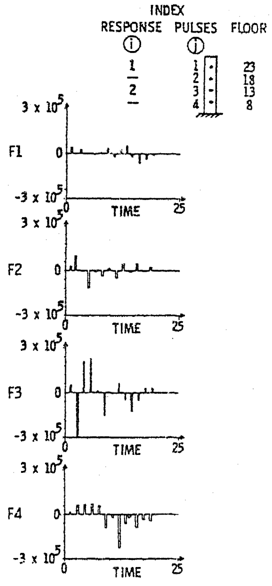
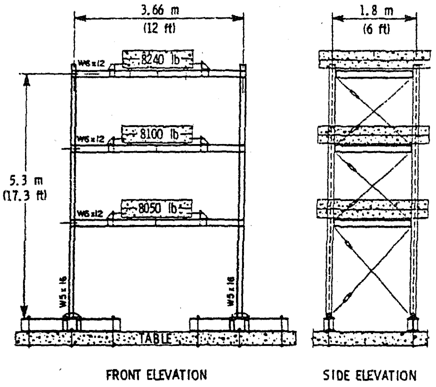


FIGURE 7. OPTIMUM PULSE TRAINS FOR 25 DOF SYSTEM

Model of UCB Frame

The test structure shown in Fig. 8 has been extensively investigated, both experimentally [12] and analytically [13] at the University of California, Berkeley. In the present study, the computer program SAP6 [14] was used to determine the mode shapes and frequencies of a linear model of this structure, and these dynamic characteristics are shown in Fig. 9.



FRONT ELEVATION SIDE ELEVATION

FIGURE 8. UCB TEST STRUCTURE [13]

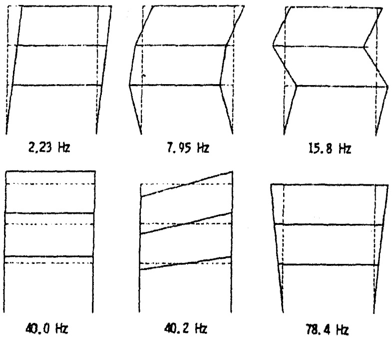


FIGURE 9. MODE SHAPES OF UCB FRAME DETERMINED BY SAP6

Pulse trains were to be applied at the three floor locations. The needed impulsive response functions were analytically determined and are shown in Fig. 10. The criteria response to El Centro 1940 earthquake was likewise analytically determined by using SAP6, and the results are shown as solid lines in response time history of Fig. 11. The adaptive random research optimization procedure was again used to determine the required pulse trains. The resulting simulated motion and the three required pulse trains are shown in Figs. 11 and 12.

This example again results in excellent agreement between the criterion and simulated response. In addition, the response spectra of various locations satisfactorily matched the criterion spectra at corresponding locations.

CONCLUSIONS

On the basis of the investigation reported herein, it is concluded that pulse-excitation techniques offer a viable alternative to large testing facilities (which have limited availability) and ground-explosion approaches (which are economically prohibitive) in simulating earthquake effects on structures, particularly when multiaxis excitation capability is needed.

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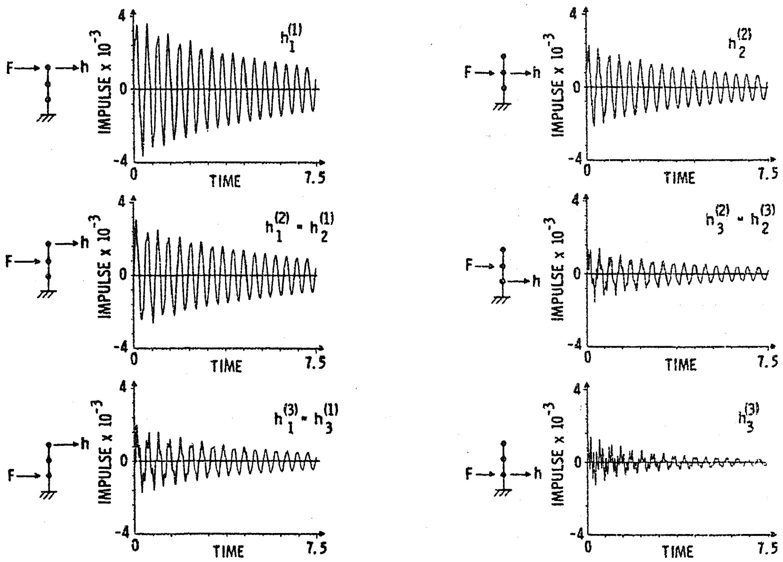

FIGURE 10. IMPULSE FUNCTIONS FOR UCB FRAME

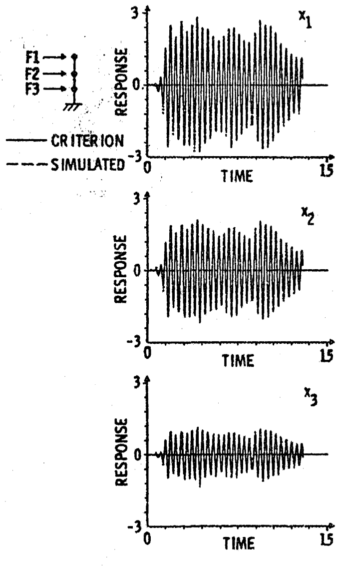

FIGURE 11. COMPARISON OF CRITERION AND SIMULATED RESPONSE OF UCB FRAME

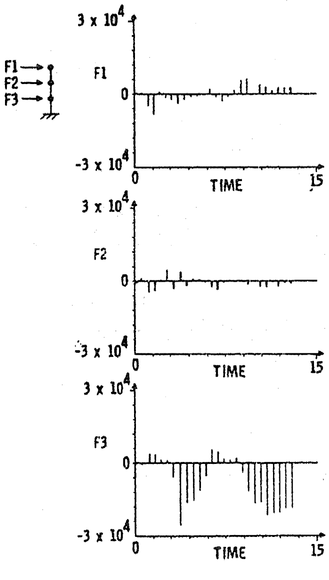

FIGURE 12. OPTIMUM PULSE TRAINS FOR UCB FRAME

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