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IDENTIFICATION OF HYSTERETIC BEHAVIOR FROM STRONG-MOTION ACCELEROGRAMS

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SUMMARY

This paper presents a new methodology for identifying the properties of hysteretic structures from strong-motion earthquake data. The method is based on determination of the generalized restoring force diagram for different mode-like components of the response. Both non-parametric and parametric identification techniques are incorporated into the general methodology. The approach can be employed even if data are available from only a small number of locations in the structure. The ultimate objective of this development is to provide a means to assess the damage to a structure following an earthquake and to predict its response to any future events.

INTRODUCTION

The most conclusive method for studying the response behavior of a structure in the nonlinear range is to measure its response to an actual earthquake. However, the analysis of strong-motion response data presents a number of difficult challenges. First, the number of response measurements is usually quite small. Frequently, only two records are available, one at the base of the structure and the other near the top of the structure. Second, since the system is nonlinear, purely linear models cannot be used successfully to treat the entire duration of the response. It is believed that the absence of well-established analytical techniques for determining nonlinear structural models from earthquake data has been a deterrent to the use of this data in the systematic study of nonlinear structural response.

DEFINING THE "MODAL" RESPONSE OF THE STRUCTURE

Let the differential equations describing the structure be expressed in the form

$$M\ddot{\underset{\sim}{y}} + \underset{\sim}{f}(\underset{\sim}{y}, \dot{\underset{\sim}{y}}) = -M\underset{\sim}{1}\,\ddot{z}(t) \tag{1}$$

where M is the diagonal mass matrix of order n, $\underset{\sim}{y}$ is the relative displacement vector of the structure with respect to its base, $\underset{\sim}{f}$ is the nonlinear restoring force vector and $\ddot{z}(t)$ is the input base acceleration. Assume that there exists a transformation of the form

$$\underset{\sim}{y}(t) = \Phi\,\underset{\sim}{u}(t) \tag{2}$$

where Φ is an $n \times m$ matrix which nearly uncouples the differential equations of motion into mode-like equations. For a nonlinear system, such a transformation may not strictly exist. That is, it may not be possible to completely eliminate all coupling, but only to minimize this coupling. However, the concept is still useful.

Next, define the *generalized modal displacement* at station i for the rth mode as y_i^r where

$$y_i^r(t) = \phi_{ir}\, u_r(t) \; . \tag{3}$$

Then, the y_i^r will satisfy differential equations of the form

$$\ddot{y}_i^r + h_i^r(y_j^s, \dot{y}_j^s) = -\beta_i^r\, \ddot{z}(t) \; ; \qquad s = 1, \ldots, m \text{ and } j = 1, \ldots n \tag{4}$$

where h_i^r is referred to as the *generalized modal restoring force* and β_i^r as the *effective modal participation factor* for station i in mode r.

In the most general case, the generalized restoring force, h_i^r, will depend upon all of the generalized modal displacements, y_j^s. However, for many structural systems, it is found that the coupling terms in h_i^r can be made very small by a proper selection of Φ. In this way, the system is practically, though not mathematically, diagonalized and it may be assumed that

$$h_i^r(y_j^s, \dot{y}_j^s) \cong h_i^r(y_i^r, \dot{y}_i^r) \; . \tag{5}$$

One way to minimize the coupling is to determine y_i^r from the data by band-pass filtering. This approach has been used successfully in the numerical examples presented herein.

The modal equations of response, equations (4), may be rearranged as

$$h_i^r(y_i^r, \dot{y}_i^r) = -\beta_i^r\, \ddot{z}(t) - \ddot{y}_i^r \; . \tag{6}$$

In this way, the modal restoring force may be defined directly from the data if β_i^r is known. This approach was first used by Iemura and Jennings.

IDENTIFICATION METHODOLOGY

System identification techniques are based on the minimization of some measure of the difference, D, between the measured and predicted response. In the present approach, the measure which is used is the root mean squared difference between the predicted and measured response in each "mode" at the time when the measured response quantity achieves a local maximum. This measure is chosen for two reasons. First, the peak response is usually the most important measure from a damage assessment or engineering point of view. Second, this approach results in considerable reduction in computational effort versus one in which the entire recorded data set is employed. Furthermore, it is found that the peak-only approach leads to very satisfactory estimates for the systems studied.

Let any response quantity with a super-hat denote the predicted value of that quantity to the measured excitation assuming a particular restoring force model, and let $\underset{\sim}{\theta}$ represent the vector of model parameters. Then, the minimization criterion for purposes of identification may be expressed as

$$D(\underset{\sim}{\theta}, \beta_i^r) \equiv \text{r.m.s.}\; \frac{[x_i^r(t_{\text{peak}}) - \hat{x}_i^r(t_{\text{peak}}, \underset{\sim}{\theta}, \beta_i^r)]}{x_{i_{\max}}^r} = \text{min with respect to } \underset{\sim}{\theta}, \beta_i^r \tag{7}$$

x_i^r can be any modal response quantity desired. The identification methodology consists of three basis elements: 1) estimation of the "modal" response quantities through band-pass filtering of the data; 2) estimation of the restoring force model; and 3) estimation of the effective modal participation factor.

Estimation of the Restoring Force Model For this step of the identification process, a value of the effective modal participation factor β_i^r is assumed based on either ambient data, numerical modeling, previous calculations, or engineering judgment. Then, a standard identification algorithm is applied using the restoring force as the variable x_i^r in equation (7). That is, $x_i^r = h_i^r$. Hence, at this step of identification process, a minimization is performed over all the local extrema of the restoring force. A non-parametric model is first used to represent h_i^r and later, a full hysteretic model is employed as discussed below.

Estimation of the Modal Participation Factor Once the restoring force model has been determined, the modal participation factor is estimated using a simple one-dimensional optimization scheme. This is a straightforward operation which can be implemented numerically with considerable efficiency. After the effective modal participation factor has been determined, the restoring force model is reidentified, and the process is continued until the change in both the model and the participation factor is less than some specified value.

RESTORING FORCE MODELS

Two nonlinear restoring force models are employed in the generalized modal identification method. The first, a nonparametric pseudo-hysteretic model is used to obtain an initial estimate of the backbone of the hysteretic restoring force and to estimate the effective modal participation factor. The second, a parametric true hysteretic model, is used to obtain the final structural model. By beginning the parametric optimization with the results of the nonparametric model, the convergence of the identification algorithm is greatly enhanced.

Four-Parameter Nonparametric Model In the initial stage of identification, it is assumed that

$$\hat{h}_i^r = a_1^r\, y_i^r + a_2^r\,(y_i^r)^3 + a_3^r\,\dot{y}_i^r + a_4^r\,(\dot{y}_i^r)^3 \tag{8}$$

In this model, a_1 and a_3 control the small amplitude behavior of the response, while a_2 and a_4 control the large amplitude behavior. This model is the simplest extension of a purely linear model. Since the modal restoring force is postulated as an explicit function of the modal displacement and velocity, no time integration of the equations of motion need be performed to carry out the identification process.

Two-Parameter Distributed-Element Model for Non-Deteriorating Structures In order to better model the hysteretic behavior of the structure, a parametric distributed-element model is used to complete the structural identification of non-deteriorating systems. The model used is the Distributed-Element model (Ref. 1). In order to be consistent with the nonparametric model, the backbone of the hysteresis curves is specified to be of the form

$$\begin{aligned} h_i^r &= b_1^r\, y_i^r + b_2^r\,(y_i^r)^3 \quad ; \qquad y_i^r \le \sqrt{-b_1^r/3b_2^r} \\ &= (2b_1^r/3)\,\sqrt{-b_1^r/3b_2^r}\,; \qquad y_i^r > \sqrt{-b_1^r/3b_2^r} \end{aligned} \tag{9}$$

The initial estimate of the model parameters is taken to be $b_1^r = a_1^r$ and $b_2^r = a_2^r$. The stiffness distribution of the sub-elements of the model may be determined uniquely from the backbone curve (Ref. 1). The hysteretic behavior of the model may be generated from the elasto-plastic behavior of the sub-elements and no additional special mathematical rules are needed to define the evolution of hysteresis loops. Since the model parameters identified during the initial stage nonparametric identification are generally very close to the optimal parameters of the parametric model, error minimization for the final stage of the identification process has been found to be very efficient.

VERIFICATION EXAMPLE

The identification approach outlined above has been verified using simulated data generated for a three-story hysteretic structure whose characteristics were chosen to approximate those of a structure tested on the shaking table at the University of California, Berkeley (Ref. 2). Three different earthquake accelerograms were used as a base excitation to generate response data for the structure. The first accelerogram, El Centro, 1940, S00E, was used to identify the structure and the second and third accelerograms, Taft, 1952, S69E, and Parkfield, 1966, N65E, were used to study the prediction capability of the identified model. All accelerograms were scaled to a peak acceleration of 0.5g in order to ensure that significant nonlinear response behavior would be observed. The base input and top floor response data only were used in the identification analysis.

Figure 1 shows the displacement response of the top mass relative to the base for the El Centro excitation as determined from the actual structure (solid) and the final hysteretic model (dashed) obtained from identification. There is seen to be very close agreement in both the amplitude and phase of the two time histories. Figure 2 shows the inter-story restoring force diagrams between floors one and two for the actual system for the El Centro and Parkfield excitations. It is seen that there is only moderate yielding for the El Centro excitation while the Parkfield excitation causes sever yielding and a resulting permanent offset.

Figure 3 shows the predicted response of the structure to the Parkfield excitation based on the hysteretic model determined from the El Centro earthquake (dashed) and the actual displacement of the structure (solid). The agreement is quite satisfactory especially considering the higher degree of yielding and the presence of permanent drift for the Parkfield excitation. All major features of the response have been captured by the model, even though a totally different excitation was used to identify the model. Further discussion of the verification example may be found in the references (Ref. 3).

APPLICATION TO REAL TEST DATA

The proposed identification methodology has been applied to pseudo-dynamic test data from a full-scale six-story steel-framed structure tested in Japan as part of the US-Japan Cooperative Research Program (Ref. 4). The excitation used in the test was the Taft, 1952, S21W accelerogram scaled to 0.5g. The input and roof response data only were used in the analysis. Figure 4 shows the final identification results for the relative acceleration and displacement response of the top floor using the two-parameter distributed-element model. It is seen that there is excellent agreement between the test data and the results predicted by the model. This is equally true for the low-frequency dominated displacement and the higher frequency acceleration time histories.

The identification methodology provides hysteretic modal restoring force diagrams for each identified mode of the structure. These diagrams show significant yielding behavior which can ultimately be related to the local hysteretic behavior of the elements making up the structural frame. Precisely how the modal hysteretic behavior should be apportioned between internal structural elements cannot be deduced directly from the model, since it is derived from measurements at only one point in the structure. However, an estimate of the internal response can be obtained using an assumed mode shape for the structure. Using an estimate of the shape of the first mode and mass distribution only (Ref. 4), the inter-story restoring forces have been computed based on one mode of the generalized modal restoring force. The result for the story between floors 2 and 3 is presented in Figure 5. The figure also shows the result obtained directly from experimental data (Ref. 5). The agreement, though not perfect, is better than might have been expected from a model based solely upon a single response measurement. The definition of the model hysteresis loops would be improved by the addition of contributions from higher modes.

CONCLUSIONS

A system identification methodology has been presented which is particularly suitable for use in analyzing strong-motion accelerograph data from structures which exhibit hysteretic response behavior. The validity of the methodology has been verified using simulated data. Application of the methodology to actual data shows that it is capable of providing an accurate representation of the hysteretic nature of structural response. The methodology proposed should provide a basis for further development of nonlinear structural identification techniques with the ultimate goal of assessing and predicting structural damage.

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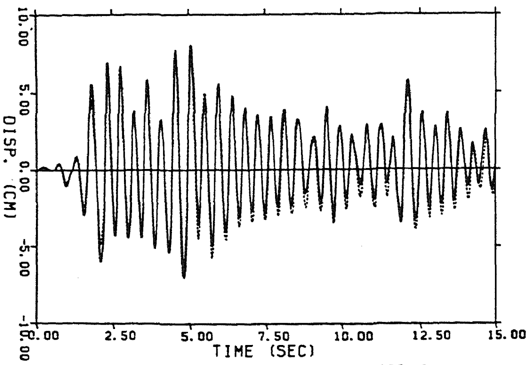

Fig. 1 Ver. Str. Roof Displ., El Centro, Identified - - - - , Actual ——

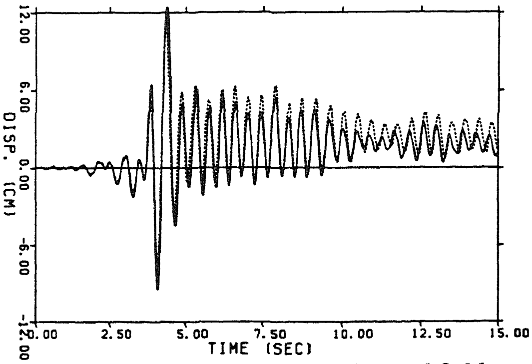

Fig. 4 Ver. Str. Roof Displ., Parkfield, Identified - - - - , Actual ——

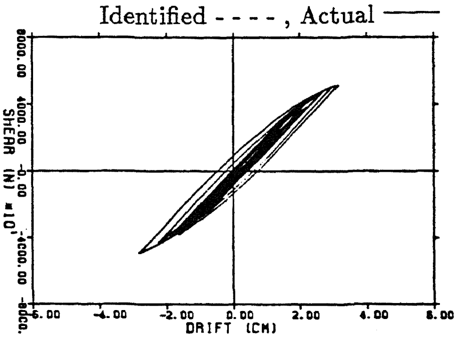

Fig. 2 Interstory Rest. Force Diag., Story 2, El Centro

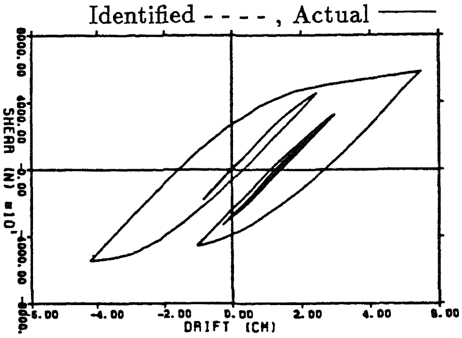

Fig. 3 Interstory Rest. Force Diag., Story 2, Parkfield

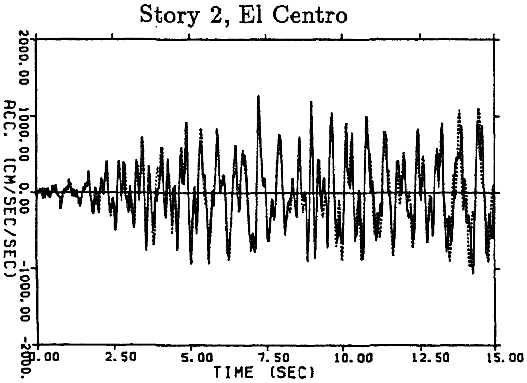

Fig. 5 Test Str. Roof Accel., Identified - - - - , Actual ——

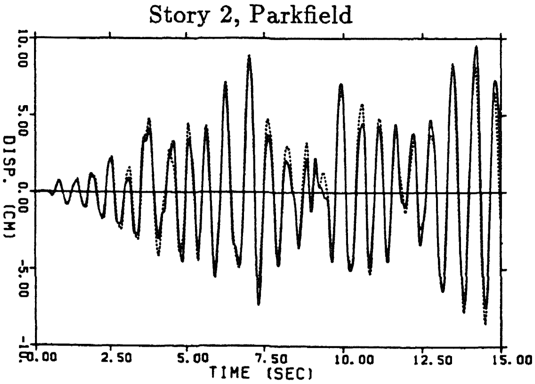

Fig. 6 Test Str. Roof Displ., Identified - - - - , Actual ——

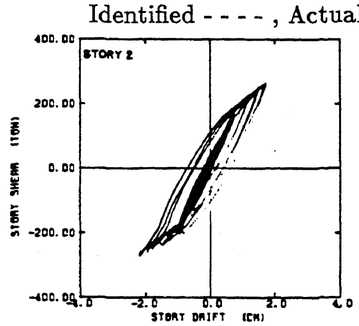

Fig. 7 Interstory Rest. Force Diag., Story 2, Experimental

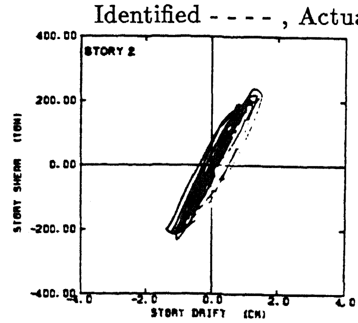

Fig. 8 Interstory Rest. Force Diag., Story 2, Identified