CE-STR-80-7
EC-80-2

SYSTEM IDENTIFICATION IN EARTHQUAKE ENGINEERING

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Supported by
The National Science Foundation
through
Grants No. PFR 7825485 and PFR 7906296

May 1980

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50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. NSF/RA-800205	2.	3. Recipient's Accession No. PB81 140667
4. Title and Subtitle System Identification in Earthquake Engineering			5. Report Date May 1980
			6.
7. Author(s) J. T. P. Yao, A. J. Schiff			8. Performing Organization Rept. No. CE-STR-80-7(EC-80-2)
9. Performing Organization Name and Address Purdue University School of Earthquake Engineering Center for Earthquake and Ground Motion Studies West Lafayette, IN 47907			10. Project/Task/Work Unit No.
			11. Contract(C) or Grant(G) No. (C) PFR7825485 (G) PFR7906296
12. Sponsoring Organization Name and Address Engineering and Applied Science (EAS) National Science Foundation 1800 G Street, N.W. Washington, D.C. 20550			13. Type of Report & Period Covered
			14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Application of system identification techniques in earthquake engineering research is described with emphasis on the damage evaluation of existing structures. Two recent developments have increased motivation to use structural identification for locating transducers for strong motion recording: the changing approach to instrumenting structures to determine their earthquake response; and the increasing development of more accurate earthquake forecasts which can result in prediction of at least some earthquakes. The report considers use of identification in the following situations involving existing structures: (1) analysis of dynamic test data; (2) analysis of strong-motion earthquake response data; and (3) analysis of post-earthquake data. Problems common to each of these applications are reviewed. An approach to resolve the uncertainty problem in analysis is suggested.

17. Document Analysis a. Descriptors

Damage assessment
Earthquakes
Computer programs
Mathematical prediction
Dynamic structural analysis
Seismic detection
Forecasting
Transducers

b. Identifiers/Open-Ended Terms

Strong motion recording

Earthquake Hazards Mitigation

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
NTIS	20. Security Class (This Page)	22. Price

(See ANSI–Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4–77) (Formerly NTIS–35) Department of Commerce

SYSTEM IDENTIFICATION IN EARTHQUAKE ENGINEERING

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INTRODUCTION

As structural engineers pursuing earthquake engineering research, our motivation and objective to apply system identification techniques are different from those of traditional control engineers because we are mainly concerned with the safety and reliability of structures. Moreover, the situations for such applications are different because of the inherent complexities in existing structural systems. In the following, an attempt is made to present a structural engineering viewpoint of this important subject area with an emphasis on the damage evaluation of existing structures.

In the classical problem (and narrow-sense definition) of system identification (e.g., see Sage and Melsa(23)[3] or Eykhoff (10), a noise-corrupted system state vector, $z(t)$, is observed along with input signal

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[3]Numerals in parentheses refer to corresponding items in Appendix I -- References

u(t), and input noise w(t). In general,

$$z(t) = h[x(t), u(t), w(t), p(t)\ v(t), t]$$

where $x(t)$ = state vector

$p(t)$ = unknown parameters of the system

$v(t)$ = observation noise

t = time

Moreover, the state vector x(t) is assumed to be governed by a (deterministic or stochastic, linear or nonlinear) differential or integral equation. Solutions of the general system identification problem consist of (a) determination of the form of the differential or integral equation, and (b) estimation of unknown parameter vector p(t), which may consist of coefficients of the system differential or integral equation as well as mean and variance values of the system noise w(t) and observation noise v(t). During these past fifteen years, such techniques have been successfully applied to obtain mathematical representations for various civil engineering structures. These resulting mathematical models are certainly more realistic than those without test data in making further analyses of the particular existing structure being studied. Several literature reviews of this subject area are available (9,15,18,22,24,25).

These tests are usually performed at small response amplitudes to avoid the exceedence of any serviceability or safety limit states (17). Consequently, the applicability of the resulting mathematical model is restricted to the linear or slightly nonlinear range of the structural behavior. Although such mathematical representations are more realistic for linear analysis of the structure under consideration, they are not generally applicable for making safety analyses involving extreme loading conditions such as tornadoes or strong-motion earthquakes. In addition, it is well known that nonlinear structural behavior is a function of the previous load-history. Therefore, it is difficult to obtain a simple mathematical relationship to simulate the nonlinear, load-dependent, and time-variant behavior of complex structures subject to natural hazards. One alternative is to assess the extent of structural damage following each catastrophic event, and then use the results of such an assessment to modify the corresponding mathematical representation (26,30).

The ultimate objective of using methods of structural identification in the field of earthquake engineering is to improve the safety and reduce earthquake damage to engineeed structures in a cost-effective manner. In this paper, the use of structural identification in the following three situations is considered: namely, (a) the analysis of test data, (b) the analysis of strong motion response data, and (c) the analysis of post earthquake test data. Problems common to each of the above applications are reviewed. In addition, an approach to one of the main problems, uncertainty in the analysis, is suggested.

STRUCTURAL IDENTIFICATION

While needs exist for further structural applications of the existing methodology for system identification, it is believed that the identification of other characteristics such as the damage state and some reliability measure, which are of more direct interest to structural engineer, should be studied. In 1978, Liu and Yao (20) presented a comprehensive literature review of damage functions and discussed the general problem of structural identification. For structural engineers, it is important to estimate the damage state at the time of the test and inspection in addition to obtaining a set of differential equations or generalized impulse response functions. Recently, Gorman (14) considered the undesirable consequence of structural damage as a measure of risk. Nevertheless, it is still difficult to clearly define the degree of damage of a prototype complex structural system which exists in the real world.

Almost all civil engineering structures are massive, stiff, and individually designed and constructed. Therefore, it is much more costly to conduct full-scale tests than other types of structures such as airplanes. Nevertheless, many such structures have been tested but usually under small-amplitude dynamic loading conditions (17,18). Recently, destructive and dynamic full-scale tests were performed on an 11-story reinforced concrete building (13) and a 3-span steel highway bridge (3). Experimental data from such full-scale destructive tests are considered to be very important in the development of a rational approach to damage assessment of existing structures (27). In addition, the application of structural identification can provide the designer-engineer with feedback information on the actual behavior of the structural system in the real world.

STRUCTURAL TESTING

While various methods of system identification can be used successfully in the laboratory, the application of these methods to real structures holds the potential for addressing some of the fundamental questions facing the profession. Modern computer methods provide a means of analyzing the basic structural system of most structures. However, the connectivity and the effect of non-structural members has a significant influence on system response. Testing, as used in this section, refers to the analysis of data obtained from low-level forced vibrations and ambient response data. Test data in this application can be characterized by long time series from several transducers. While the complexity and cost of performing full-scale tests is high, its application to the following areas holds great potential.

Two recent developments provide an increased incentive to use structural identification for locating transducers for strong-motion recording. First, the approach to instrumenting structures to determine its earthquake response is changing. Instead of placing a very limited number of transducers at prescribed locations (basement, mid-level and top) of a structure, more transducers are being distributed so that they will measure the response better. A logical extension of this is to use structural identification to aid in locating transducers. The second development is that with increased efforts in earthquake prediction there will probably be a time when at least some earthquakes will be predicted. This provides the opportunity to concentrate instrumentation to measure structural response and creates a need to determine pre-earthquake response and transducer deployment.

Fundamental to the response of a system is its ability to dissipate energy. While dissipation during low-amplitutde and high-amplitude response will in general be quite different, and understanding of how design and detailing influences dissipation will aid in the ability of its being able to be designed into the system.

In these two applications which have been suggested, it must be realized that low-level test results are being used to obtain high-amplitude response data. Thus, there is a high degree of uncertainty in the mathematical model used to represent the structural system.

ANALYSIS OF EARTHQUAKE RESPONSE DATA

A significant benefit resulting from the use of structural identification is in the evaluation of real earthquake data. This provides the potential of finding out how systems and materials behave at large response levels. Several distinct applications can be identified although they overlap each other to a degree. In general, earthquake response data will be characterized by records of short duration from a limited number of transducers. It should be emphasized that the analysis of response data is a supplement to rather than a substitution for field study of damage by structural engineers. In the following, three specific applications are discussed:

(a) It seems to be desirable to identify the character and location of nonlinear elements within the system. The objective here would be to determine which elements contribute to dissipating energy so that they can be incorporated into designs.

(b) It is always difficult to determine the sequence of events and distinguish the primary causes of damage from secondary failures. Thus, structural identification applied to earthquake data may provide a means of identifying failure mechanisms.

(c) The analysis of system response records using structural identification may provide a means to assess structural damage. Clearly these methods can be used to indicate changes in the response.

There are several major problems to these above mentioned types of analyses. The most interesting data will be those from structures responding in their nonlinear range. Thus, methods must be applicable to nonlinear analysis or be robust enough to be applied to nonlinear response. Piecewise linear methods have been used. Two of the most severe restrictions in evaluating earthquake data is that the excitations will be random in character and the records will be relatively short. Thus, from a statistical point of view, these analyses will have large uncertainties. Finally, there will be uncertainties associated with the system models since the structure will exhibit many different types of nonlinearity.

POST EARTHQUAKE TESTING

Ambient and forced vibration test and other specialized tests after an earthquake can serve several purposes. They are reviewed as follows:

(a) In the aftermath of a severe earthquake, there exists a need to determine whether a given structure can be occupied prior to detailed inspection and possible repair. Analysis of ambient vibration tests in conjunction with pre-earthquake data and cursory inspection may provide the means for determining if the structure can be occupied.

(b) An extension of structural integrety evaluation is the assessment of damage. Analysis could be used to indicate if restoration should be attempted and could indicate the location and type of damage which is present. For these evaluations, specialized methods, e.g., those associated with nondestructive testing, should be used.

The above use of structural identification will again yield data which exhibit a high degree of uncertainty as to its interpretation.

APPROACHES TO UNCERTAINTY

An element which has been common in the above uses of structural identification is the uncertainty of models and interpretation of results. First, it is vital to recognize the large uncertainties that are involved. At the present time most authors state the means of results obtained using structural identification but give no indication of their variability. While formal methods of analysis of variance may not be available, frequently simulation is used without assessing the variability of results. The large variability of results suggest the need for special methods of analysis.

Fu and Yao (12) considered the problem of damage assessment in terms of pattern recognition. In the theory of pattern recognition (1,21), data are collected from a physical systems such as an existing building structure. These data would include traditional response data from accelerometers as well as other observations and inspection data such as size, number, and location of cracks. A feature space is then extracted. Finally, a decision function or classifier is applied to obtain the classification, which in our case is the damage state. As an example, the reduction in natural frequency which can be determined with the application of classical system identification techniques can be used as a feature (4,5,7,8,11,16). As another example, the size, number, and location of cracks can be used as another feature (2).

According to Zadeh (31,32), as the complexity of a system increases, our ability of making precise and yet significant statements concerning its behavior diminishes. Consequently, the closer one looks at a real-world problem, which is usually complex, the fuzzier its solution becomes. The application of fuzzy sets in solving civil engineering problems was reviewed recently (28,29). Most civil engineering structures are indeed complex systems, the behavior of which can not be easily and clearly described.

In a recent paper (29), fundamental elements of the theory of fuzzy sets are given by Zadeh (32) and Kaufmann (19) are summarized along with several structural engineering examples from Yao (28) and a simplified version of an example on structural reliability from Brown (6). An attempt was then made to apply the theory of fuzzy sets to the complex problem of damage assessment of existing structures.

CONCLUDING REMARKS

There exists a need for researchers in this subject area to include in their results an estimation of the variability involved. The large variability of these results is not generally acknowledged by many investigators at present.

The available techniques for system identification has now grown to such an extent that several methods are applicable to any given situation. The computer implementation of most system identification methods is a major undertaking, and often includes "tricks" which may not be known to users other than the particular investigators who developed such programs. Thus, it is very important to properly document the software for each practical method of system identification. In this manner, the robustness of various methods can be evaluated through appropriate comparisons of these methods against one another in real-world situation.

Results of system identification studies are considered as a part of the input to the process of structural identification as defined herein. Generally, necessary data can be generated from various testing and inspection procedures. The processes of data reduction and decision making for the purpose of damage assessment remain to be studied further. In this regard, the application of pattern recognition and fuzzy sets shows promise and requires further study.

ACKNOWLEDGMENT

We wish to thank the National Science Foundation of U.S.A. for the continued support, without which this paper could not have been prepared. Vicki Gascho typed this manuscript.

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