Dynamic testing of nuclear power plant structures—an evaluation

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FOREWORD

At the request of the US Nuclear Regulatory Commission (NRC), Lawrence Livermore Laboratory (LLL) evaluated the applications of system identification techniques to nuclear power plant structures and subsystems. These techniques involve exciting the structure and measuring, digitizing, and processing the time-history motions that result throughout the structure. This report summarizes the overall results of FY78 and FY79 work, which can be divided into three main areas:

- Examination of the feasibility of safely exciting a nuclear power plant structure and accurately recording the resulting time-history motions.
- Analytical qualification of a particular set of LLL computer programs for use in confidently extracting the modal parameters from the time histories. The qualification will also serve as a benchmark for evaluating other such computer programs.
- Study of how the extracted modal parameters can be used best to evaluate structural integrity and analyze nuclear power plants.

The overall study was conducted for the NRC Office of Nuclear Reactor Research, Reactor Safety Research Division, Mechanical Engineering Research Branch by engineers in both the Mechanical and Electrical Engineering Divisions at LLL. Portions were subcontracted to three outside companies:

Agbabian Associates (AA)
El Segundo, California

ANCO Engineers, Inc. (ANCO)
Santa Monica, California

Structural Measurement Systems, Inc. (SMS)
Santa Clara, California

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ABSTRACT

Lawrence Livermore Laboratory (LLL) evaluated the applications of system identification techniques to the dynamic testing of nuclear power plant structures and subsystems. These experimental techniques involve exciting a structure and measuring, digitizing, and processing the time-history motions that result. The data can be compared to parameters calculated using finite element or other models of the test systems to validate the model and to verify the seismic analysis. This report summarizes work in three main areas: (1) analytical qualification of a set of computer programs developed at LLL to extract model parameters from the time histories; (2) examination of the feasibility of safely exciting nuclear power plant structures and accurately recording the resulting time-history motions; (3) study of how the model parameters that are extracted from the data be used best to evaluate structural integrity and analyze nuclear power plants.

SUMMARY

Testing of nuclear power plant structures to obtain modal parameters such as damping, natural frequencies, and mode shapes is both proven and viable. Excitation techniques exist that will safely set the structures in motion, and measurement and instrumentation methods are available that will accurately record and analyze the resulting time-history response signals. A set of LLL computer programs was developed to extract the modal parameters from measured time-history response signals. These parameters can be used to validate or improve mathematical models of the structure, or they can be monitored for changes that indicate degradation or change in the integrity of the structure. The computer programs have been analytically qualified and will be made available to the NRC for public use. The programs can be used for extraction of modal parameters from test data, or their qualification can serve as a benchmark for the evaluation of other computer programs.

INTRODUCTION

A mathematical model is usually constructed for the study of a physical system or phenomenon. If accurate, the model can be used to examine the behavior of the system when it interacts with its environment or other systems. There are several reasons why one studies the mathematical model of a system rather than the physical system itself, including:

- Faster, less expensive analysis.
- Insight into the characteristics of the system gained by solving the mathematical equations. For example, a singularity in the solution of a mechanical vibratory system indicates a natural resonance.
- Practicality--for example, the study of missile impact effects on a nuclear power plant containment structure.

At issue in such studies is whether or not the mathematical model accurately represents the physical system. The only way to check is by experiment; that is, one performs the same (usually simple) experiment on both the physical and analytical models and then compares the results. In the study of nuclear power plants, an important question is how will the plant, or some subsystem therein, survive an earthquake or some other extreme load? To answer this question, the system is mathematically modeled, and the model is subjected to a simulated earthquake. The calculated motions or stresses are then compared to those allowed by codes or other criteria to determine the structure's chances of survival. However, as previously mentioned, the model must be experimentally validated if we are to have confidence in these results.

Many nuclear power plant structures are modeled using finite element methods. Dynamic analysis of a finite element model yields the modal parameters--natural frequencies, damping, and mode shapes--of a linear structure. Finite element methods are also well suited to the analysis of nonlinear behavior. As described below, simple nondestructive tests can be performed that will yield the actual modal parameters of a structure for comparison with those predicted by the mathematical model. These experimental modal parameters also have several other interesting and useful applications that are discussed in this report. If nonlinear response is of interest, system parameters such as mass, stiffness, and damping can be determined from experimental data by relating measurements to mathematical predictions and selecting the values of the parameters that result in acceptable correlation.

The modal parameters of a structure can be experimentally obtained from a process known as system identification, which basically comprises:

- Applying a forcing function(s) to a structure that results in a transient vibratory motion.
- Measuring and recording these motions as time-history signals at several locations along the structure.

Processing these signals on a digital computer to extract the modal parameters of the structure.

Eccentric mass shakers, which generate a slowly swept sinusoidal shaking motion, have long been used to excite structures. However, as recently as 15 years ago, the resulting time histories had to be recorded in analog form and processed by hand. A major breakthrough occurred around 1970 when digital recording and processing equipment became readily available and permitted the direct recording and analysis of the time histories in more accurate digital form. This breakthrough also opened the door to several other system identification techniques.

The rest of this report summarizes the overall results of our FY78 and FY79 work to evaluate the applications of system identification techniques to nuclear power plant structures and subsystems. This work is divided into three main areas:

- Examination of the feasibility of safely exciting a nuclear power plant structure and accurately recording the resulting time-history motions.
- Analytical qualification of a particular set of LLL computer programs for use in extracting the modal parameters from the time histories with confidence. The qualification will also serve as a benchmark for evaluating other such computer programs.
- Study of how these extracted modal parameters can be used best to evaluate structural integrity and analyze nuclear power plants.

However, it must be clearly understood that this report is only a summary of results and contains little detail and rigor. The reader is strongly urged to study each subcontractor report, reproduced on fiche in a pocket of the back cover of this report, for a complete understanding of these results.

FEASIBILITY OF EXPERIMENTALLY TESTING NUCLEAR POWER PLANTS

To experimentally test a nuclear power plant some forcing function must set the structure in motion. Because nuclear power plant structures are so massive, these forces must be large, which raises two questions:

Can such large forcing functions be physically realized?

If so, can they be applied to the structure safely, that is, without causing damage or otherwise impairing the licensibility of the plant?

For answers we looked to two companies that have demonstrated experience in the field of testing large and massive structures, Agbabian Associates (AA) and ANCO Engineers, Inc. (ANCO). Their independent studies both reached the same conclusions. Namely, not only is it possible to test nuclear power plant structures safely but, in fact, such tests have already been conducted.

LLL contracted both AA and ANCO to assess the methods and benefits of dynamically testing nuclear power plant structures. The resulting reports (Refs. 2 and 3, and Appendixes B and C of this report, respectively) address such topics as:

- Methods of excitation
- Safety considerations and allowable excitation levels
- Discussion of system identification techniques
- Extrapolation of parameters to higher excitation levels
- Instrumentation and measurement systems
- Budget and scheduling guidelines.

These reports are supplemented by Sec. 3 of the report by the third subcontractor Structural Measurement Systems (SMS). The SMS report (Ref. 1), which is included on fiche as Appendix A of this report, provides a general discussion of modal testing techniques. Although the SMS report does not specifically deal with nuclear power plant testing, it provides insight by pointing out the advantages and disadvantages of various excitation, instrumentation, and signal-processing methods.

The overall conclusion reached in these reports is that testing of nuclear power plant structures would be beneficial. In the following six sections, we discuss each topic listed above. For the most part, the points made in these discussions are taken from the reports by AA and ANCO and supplemented by sections of the SMS report. Again, the reader is strongly urged to read each report--provided on fiche as Appendixes A, B, and C to this report--for the greater detail they contain.

EXCITATION TECHNIQUES

The ideal way to excite a full-scale structure is by the use of buried high-explosive charges. One advantage of this method is the proven high levels of excitation that can be reached--peak response levels ranging from 0.001 to 1.0 g. Also, if seismic verification of a structure is the purpose of testing, then this form of excitation most resembles that due to an earthquake (i.e., the energy is transmitted to the structure through the soil and foundation). Both the frequency content and the amplitude of the ground motion, or base excitation, can be controlled by the sizing, spacing, depth of burial, and timing of the charges. The biggest drawback to explosive excitation is the possible damage to seismic Category III nuclear power plant structures and nearby unrelated structures. Therefore, this type of test is very site dependent, and the final decision must be made by the plant owner.

When safety or other considerations prohibit the use of explosive charges, it is recommended that exciters be placed directly on the structure. One disadvantage of this approach is that high levels of excitation are not easily achieved. Again, if seismic verification is the purpose of the testing, this approach does not impart the energy to the structure in the same manner as does an earthquake. However, many times this may be the only way that a plant owner will permit testing. There are two different approaches to excitor-based testing, both field-proven:

- Use eccentric-mass sinusoidal shakers and normal mode analysis.
- Use pulsers--devices that can provide an excitation time history consisting of a series of pulse functions--and transfer-function modal-parameter-extraction techniques.

Basically, the normal mode method excites the structure with a narrow-frequency-band signal and extracts the modes one at a time. On the other hand, the transfer function method excites the structure with a wide-frequency-band signal and extracts the modes several at a time using various curve fitting techniques. In general, the disadvantages of one method are the advantages of the other. The normal mode method offers the following advantages relative to the transfer function method:

- Higher excitation levels are possible because all the available energy is concentrated at a single frequency.
- In use longer, it has more testing experience available.

- The amplitude and frequency of the input signal can be very accurately controlled (to within 1%).

The transfer function method has advantages relative to the normal mode method, including:

- Several modes are extracted simultaneously; hence, it is usually faster.
- Better performance when the modes are closely spaced.
- Usually requires less measurement equipment.
- A variety of input forces can be used (pulsed, random, rapidly swept sine, ambient, etc.).

Sections 3.1 and 3.2 of the SMS report (Ref. 1 and Appendix A) present a more complete description and comparison of the two methods.

Internal equipment or substructures such as a piping system can be tested in much the same way as an overall structure; that is, exciters can be placed directly on the equipment to set it in motion, and then either a normal mode or transfer function analysis is performed. It is also possible to excite a substructure with a snapback or step relaxation technique in which an inextensible, light-weight cable, attached to the structure, is used to preload it to some acceptable force level. When the cable is severed, the structure "relaxes" with a force step, and its transient response is recorded and processed using curve fitting techniques. A single snapback cable may not be able to excite all the modes of interest. However, if several cables are used to deform the structure and are released simultaneously, this problem can be circumvented.

SAFETY CONSIDERATIONS AND PERMITTED EXCITATION LEVELS

In its report (Ref. 2 and Appendix B), ANCO makes the philosophical statement: "The safety requirement for dynamic testing of a nuclear plant is straightforward; response amplitudes which might damage or otherwise impair the licensability of the subject plant must be avoided." Another observation made is that a nuclear power plant is expected to operate during and after an operating basis earthquake (OBE), a design earthquake that might occur several times in a plant's lifetime. Each plant has its own OBE criterion, which depends upon its location and construction. This OBE criterion can be used to obtain an estimate of the permitted excitation levels; that is, if a plant is

designed to survive the OBE, then certainly some fraction (up to 100%) of the OBE excitation level should be considered safe for testing.

Used for testing, buried explosives would be designed to simulate the desired fraction of the OBE. However, nearby vulnerable structures must be protected by proper design of the charge array (i.e., focus most of the energy toward the plant and away from the other structures) and by the use of barrier trenches.

When excitors are attached directly to the structure for testing, the input force does not come through the soil and foundation, and the resulting response amplitudes must be calculated. Often this can be accomplished via heuristic arguments or by "back-of-the-envelope" calculations. However, more credibility can be obtained by constructing a mathematical model of the structure. Both ANCO and AA believe that any comprehensive test plan should include such a model to provide insight into where to locate the excitors and measurement instruments as well as to calculate the expected response amplitudes.

Note that the OBE level pertains mainly to seismic Category's I and II structures and equipment, which must survive for the plant to continue operating safely. Category III structures or equipment, such as an office building, are not directly related to the safe operation of the plant and are not necessarily designed to survive the OBE. Consequently, Category III structures or components may suffer some damage during a test. While there are no critical safety issues involved with this type of damage, the cost of repairing or avoiding damage must be taken into account. The plant owner must weigh the cost of repairs against the benefits of verifying the plant's seismic design.

SYSTEM IDENTIFICATION TECHNIQUES

The purpose of testing a structure is to provide response data. The purpose of system identification is to extract from this response data those parameters that can be related to the physical behavior, properties, and integrity of the structure. More specifically, these parameters can be used to:

- Construct mathematical models of the structure, which can be exercised to predict the structural response to such extreme loadings as an

earthquake.

- Obtain values for such inherent properties of the structure as natural frequencies, damping, stiffness, etc.
- Indicate changes that might reveal impending failure of or damage to the structure.

In general terms, system identification is a procedure that assumes a particular form for a mathematical model to describe a physical system (in our situation the system is a structure). The equations used in the model contain various parameters. For example, the parameters in the equation of motion of a single-degree-of-freedom mechanical oscillator are the mass, spring, and damping constants. The system identification process finds the best set of parameters that actually describes the system by systematically varying the parameters until the model response matches the actual system response.

For a linear structural system, there are two commonly used mathematical models. One is the finite element type, which consists of a set of simultaneous second order differential equations that represent a "force balance" among the inertial, dissipative, restoring, and externally applied forces on the structure. Finite element models of nuclear power plant structures are often used in load analyses to determine internal stresses and strains that result from external forces and in dynamic modal analyses to identify the resonant frequencies and mode shapes of the model's modes of vibration.

The other type of model, which is usually based on actual measurements of input forces and responses, characterizes the dynamics of a structure in terms of its modes of vibration. This type of model is called a time-domain structural dynamic model and resembles the finite element model in its mathematical representation. The difference is that the structural dynamic model is, in principle, an exact model of the structure's dynamics, if it is generated from measurements. Section 2.1 of the SMS report (Ref. 1 and Appendix A) provides an excellent description and comparison of the two models.

When system identification is performed on the finite element type model it is often called model modification, and it is called eigenparameter identification when performed on the structural dynamic model. System identification using a structural dynamic model is useful because it produces natural frequencies, damping values, and mode shapes--physical parameters that are familiar to designers and are often used as design tools. These

parameters can also be used to produce transfer-function models for predicting response motions. The PARET computer programs developed at LLL use this eigenparameter identification approach.⁴

When sufficient nonlinearity in the structural response occurs, the model modification method may be used in lieu of eigenparameter identification. The model modification technique is useful because it produces the mass, stiffness, and damping parameters used in finite element computer programs. Both 2A and ANCO recommend that this type of identification process should use a Bayesian estimation technique to determine the best parameters. Another strong point of this Bayesian technique is that it can also be used with nonlinear mathematical models.

EXTRAPOLATION OF PARAMETERS TO HIGHER EXCITATION LEVELS

The NRC specifies the damping parameter values that may be used in the dynamic analysis of nuclear power plants. Regulatory Guide 1.61 (R.G. 1.61) gives these values as a percent of critical damping.⁵ These values are specified at excitation levels for both the OBE and the safe shutdown earthquake (SSE, approximately twice the level of the OBE) and are both site and equipment dependent. As noted above, plants will rarely, if ever, be tested at the OBE level. Consequently, the damping values (as well as other parameters) obtained by low-level-excitation tests must be somehow extrapolated to the OBE levels and above.

If nuclear power plant structures were truly linear, these damping values would not be a function of excitation level; consequently, the values obtained from low-level tests could be directly used for high-level excitation analysis. However, nuclear power plant structures may respond nonlinearly. Some of the sources of the nonlinearities are

- Soil-structure interaction. Energy is absorbed by the surrounding soil media by hysteresis and radiated away from the oscillating structure.
- Inelastic behavior of the structural components at high levels of excitation (material nonlinearities).
- The action of snubbers when large displacements occur at high levels of excitation (geometric nonlinearities).

- Stress response of other nonlinear equipment and subsystems, resulting in an interaction between parent structures and equipment acting like energy absorbers.

It is generally believed that the damping value increases with increasing excitation level. Consequently, there is some concern that low-level testing will produce a damping value that is lower than the R.G. 1.61 value specified at a higher (OBE) level. Experience indicates that this is not necessarily the case. In fact, even at low levels of excitation the R.G. 1.61 values can be satisfied. In its report (Ref. 2 and Appendix B), ANCO summarizes several case histories for both containment structures and equipment, and shows that the damping is above the R.G. 1.61 values in these studies. Also, in a recent test performed by AA at Rocky Flats, Colorado, on massive plutonium-handling facilities, reasonably high damping values (8-10% of critical) were obtained using low-level, pulser-excitation techniques (0.001 g).

Although acceptable damping values can be obtained at low excitation levels, it is still desirable to extrapolate these results up to and beyond the OBE level. ANCO and AA offer two different ways to do this, as discussed below.

ANCO attacks the extrapolation problem by performing linear studies at several different levels of excitation, ranging from very low to as high as the plant owner will permit. For each level the desired parameters are extracted and recorded. When all the test results are obtained, a polynomial curve is fit to them using least-squares techniques. The result is a formula that describes a parameter (usually damping) as a function of the excitation level. This formula can be used with confidence to interpolate the parameter value within the domain of the polynomial fit. It can also be used with much less confidence to extrapolate the parameter value outside the domain up to and beyond the OBE level. The closer to the OBE level that the test can be performed, the more the confidence in the extrapolation.

AA reasons that the parameters of interest for nonlinear structures will depend not only upon the level of excitation but also upon the form of the excitation (sinusoidal, impulse, random, etc.). They recommend the use of a nonlinear model and an excitation function that is similar (in form, not necessarily level) to an earthquake. Sections 2 and 5 of the AA report (Ref. 3 and Appendix C) describe this plan in detail. It is briefly

summarized as follows:

- Estimate the parameters of an earthquake that can be expected to occur in the vicinity of the nuclear power plant.
- Design a high-explosive-charge array that will result in a ground motion similar to that of the expected earthquake (the level will not necessarily be that of the earthquake).
- Detonate the charge array and record the resulting response motion of the structure for subsequent processing using a nonlinear model and Bayesian techniques.
- Use the nonlinear model to extrapolate the response of the structure (as well as the parameter values) up to and beyond the OBE level.

When explosive charges are prohibited, AA offers an interesting alternative. Basically, they design an array of pulsers (such as cold gas rockets) to be attached directly to the structure. The pulsers are timed and fired to produce response motions like those that would result from the expected earthquake. While this method has been analytically demonstrated, it has not yet been physically demonstrated. However, under a grant from the National Science Foundation, Fred Safford of AA plans to perform such an experiment in 1980.

While both AA and ANCO offer reasonable solutions to the nonlinear problem, much more research is still needed. Their techniques should be applied and additional verification obtained whenever possible on decommissioned plants, scale-model plants, or plant sites at which high excitation levels will be permitted.

INSTRUMENTATION AND MEASUREMENT SYSTEMS

In their reports, ANCO (Ref. 2, Sec. 6), AA (Ref. 3, Sec. 7), and SMS (Ref. 1, Sec. 3.4) provide general discussions of the required instrumentation and data processing systems. The main elements of a typical measurement system and their functions are as follows:

- Transducer to convert response motion to an electrical signal.
- Amplifiers/attenuators to modify signal amplitude to desired level.
- Filters to remove unwanted information from the signal.
- Digitizer to convert signal from analog to digital form.
- Tape/disc to store data for subsequent processing.
- Cables to interconnect the above elements.

The reports briefly describe the operation and characteristics of the above elements. For nuclear power plant applications, a measurement system must be able to handle frequencies from 0.5 to 30 Hz and acceleration levels from 0.001 to 1.0 g. It is also strongly recommended that an on-site computer be used to evaluate the data as it is taken.

BUDGETING AND SCHEDULING GUIDELINES

The testing of a nuclear power plant can range anywhere from a simple monitoring of the ambient response motion of one component to a full-scale test of the containment structure using buried explosives. Consequently, the cost can range from a few thousand to over a million dollars. Similarly, the time required can be anywhere from a few days to well over a year. Most tests will fall somewhere between these two extremes, and their cost and time must be estimated on an individual basis. Another important cost factor is that of down time. In other words, how long must the plant be shut down, and, consequently, how much revenue will be lost while these tests are being performed?

A test plan can be roughly divided into three phases:

- Phase I: Planning. The test objectives and goals are carefully reviewed to determine the best way that they can be achieved. We recommend the close cooperation during this phase between the analyst and experimentalist in the construction of a mathematical model of the structure to be tested. This model helps in the location of transducers and exciters by providing insight into the expected behavior of this structure. It can also be used to perform safety studies in predicting response amplitudes.
- Phase II: Measurement. The experiments planned in Phase I are performed. It is possible that unexpected results obtained in this phase may require a return to Phase I for reevaluation.
- Phase III: Data Analysis. Experimental data are rigorously analyzed, and a report is written describing the results and conclusions.

ANALYTICAL VERIFICATION OF SYSTEM IDENTIFICATION CODES

The structural system parameters may be extracted from the response data by using one of several system identification computer programs that are available at LLL and other laboratories, universities, and private companies. Although these computer programs have been successfully used for some time now, there is no published documentation of their performance accuracy. Also, many of the commercially available computer programs are proprietary. For these reasons, the NRC requested that we analytically evaluate the accuracy of LLL computer programs and then make them available to the general public. Note that parameter identification of nuclear power plant structures should not necessarily be limited to the use of these particular computer programs. Although they will be made available for general use, they will also serve as a benchmark for judging and qualifying other computer programs. That is, the data used in this qualification process will be made available with the performance evaluation methodology. Therefore, other computer programs can be evaluated by repeating a similar analysis of the same data.

As previously noted for structural systems there are two commonly used mathematical models for parameter identification schemes. They are eigenparameter identification and model modification techniques. While some attention was given to the model modification technique in our study,⁶ this effort was primarily an exploration and justification for future research projects. Our computer program verification work was primarily aimed at studying the performance of two particular eigenparameter identification computer programs because these are the types most commonly used to date.

Response data can be analyzed in either the time or frequency domain. Therefore, we chose to evaluate both time-domain and frequency-domain computer programs. The issues addressed were

- How well do the computer programs perform in the presence of measurement noise?
- Which approach is superior--time or frequency domain?
- How is the performance of the computer programs affected by the spacing of the modes?

The study was accomplished by analytically generating several time-history signals for which the true modal parameters were known. These time histories ranged from widely spaced modes with spacing factors-- $2(w_n - w_m)/(w_n + w_m)$ for frequencies w_n and w_m --of 100% to closely spaced modes with spacing factors of 6%. These signals were then polluted with various levels of simulated measurement noise and the ability of our computer programs to extract the parameters from these noisy data was evaluated. The details and results of this study are presented in Ref. 7 (Appendix D). The main findings are

- We were unable to detect any substantial difference in performance between the time- and frequency-domain computer programs; consequently, we cannot recommend the use of one over the other. That decision is left to the user and will, no doubt, be based on personal preference for frequency- or time-domain analysis.
- Performance of the computer programs is not a function of the modal spacing, at least down to a spacing factor of 6%. That is, the programs perform equally well for closely and widely spaced modal signals.
- Computer program performance was defined in terms of two statistical quantities. One is percent bias (PB), which is defined as $100 \times (w - u)/w$, where w is the true value and u is the value obtained by the computer programs. The other is the coefficient of variation (CV), defined as the standard deviation divided by the true value. Reference 7 contains more details about the CV.
- The performance of the computer programs was clearly an inverse function of the signal-to-noise ratio; that is, as the noise level increased, the performance decreased. Table 1 lists the average performance of the computer programs as a function of the signal-to-noise level.

TABLE 1. Estimates of the accuracy of PARET computer programs for various signal-to-noise (S/N) ratios, from Ref. 7 (Appendix D).

S/N ratio	<u>Frequency</u>		<u>Damping</u>	
	PB ^a	CV ^b	PB	CV
100	0.04	3.2×10^{-4}	1.2	2.5×10^{-2}
70	0.04	3.2×10^{-4}	1.5	3.0×10^{-2}
40	0.02	5.3×10^{-4}	1.7	5.0×10^{-2}
20	0.04	$10. \times 10^{-4}$	2.3	$10. \times 10^{-2}$
10	0.10	$21. \times 10^{-4}$	3.3	$20. \times 10^{-2}$

^aPercent bias.

^bCoefficient of variation.

PRESENT AND FUTURE APPLICATIONS OF SYSTEM PARAMETERS

In this section, we discuss the ways in which the system identification parameters can be used in the analysis and evaluation of nuclear power plant structures. This discussion includes both applications that are currently possible and those that will soon be possible but still require more research or study.

Presently, a prime use of these parameters is to validate or improve mathematical models of structures. Once validated, these models can be reanalyzed to verify the original seismic design of nuclear power plant structures. The validation of a linear model is straightforward. Most linear models can generate the modal parameters of the structure, which can be compared to the experimental modal parameters obtained using system identification techniques. This is obviously a go or no-go situation in which the results will either agree (and the model is validated) or disagree (and the model is invalidated). If they disagree, there are at least two remedies:

- Use the experimentally obtained modal parameters to generate a "transfer function" mathematical model that will better predict response motions.
- Change the original model parameters by either trial and error or by using statistical modeling techniques so that agreement is obtained.

As discussed in a previous section, it is also possible through model modification analysis to obtain the desired model parameters directly from the response data by using Bayesian techniques or Kalman filters. An advantage of this approach is that it can be applied to both linear and nonlinear models. Our research efforts were partly aimed at demonstrating the feasibility of using model modification analysis to estimate the structural parameters, validate the design of structures, and detect structural failure. The results of this effort are presented in Ref. 6.

Another promising use of the modal parameters of a structure is for predicting damage or structural integrity degradation by monitoring changes in the modal parameters. It is well-known that the physical properties of a structure, such as mass and stiffness, determine its modal parameters. Consequently, if there is a change in the physical properties, some modal parameters will shift. For example, the stiffness of a particular member may change due to a crack. Even though the modal parameters of a nonlinear structure vary with the excitation level used to measure them, a change in the

physical properties of the structure will usually manifest itself as a change in the modal parameters at all excitation levels. Therefore, a search for shifts in the modal parameters can be conducted at low levels of excitation.

To determine the state of the art in predicting damage or structural integrity degradation by monitoring changes in the modal parameters, LLL contracted SMS to conduct a literature survey and to interview selected experts who have conducted research in this area. The results of the study, which are summarized in the remainder of this section, are presented in Ref. 1.

Based on personal communication with Sheldon Rubin of Aerospace Corporation, El Segundo, CA, SMS broke the problem into three subproblems:

- Can we define what we mean by failure, or can we determine when the degradation of the structural integrity has become intolerable?
- Can we monitor the structure to detect this intolerable failure?
- Can we measure the vibrational response and process the data with instrumentation sufficiently accurate to detect the failure?

SMS cited several examples of how the changes in a structure's integrity, or properties, resulted in shifting of the modal parameters. One dramatic example involved the testing of concrete beams to destruction by dropping weights on them.⁸ The investigators plotted the changes in the modal frequencies of the beams at various stages of failure. Shifts in these frequencies indicated some form of "failure" long before any visible signs of cracks appeared. SMS also cited the work of Ibanez et al. in which a modal survey was performed on some electrical distribution equipment to collect data for seismic modeling.⁹ The researchers found that a slight reduction in mounting bolt tension caused dramatic changes in the modal parameters.

In both cases above, the findings clearly indicate that the integrity of a structure can be monitored by noting changes in its modal parameters. However, the real question is "suppose a modal parameter changes, can we say how bad, or even where, the failure that caused this is?" As it turns out, this is a subjective decision-making task since the assessment of acceptable damage must account for many factors other than simply a shift in the modal parameters. Such a shift clearly signals that something is happening to the structure, which, therefore, should be examined more closely. It is generally believed that the vibration signals from a mechanical structure are useful indicators of physical damage in many cases, but alone will not conclusively reveal significant damage to the structure. Additional techniques are

necessary for such a positive determination.

SMS grouped the material surveyed into four main areas:

- Nuclear power plants,
- Other large structures (buildings and bridges),
- Rotating machinery,
- Off-shore platforms.

The published results in the first two areas dealt, for the most part, with obtaining modal parameters in order to validate or improve the mathematical model of the structure. For nuclear power plants, there was also considerable information on the so-called Loose Parts Monitoring Systems, which detect amplitude changes in the time or frequency spectrum and trigger an alarm when such a change occurs.

By far the largest number of integrity monitoring systems are in use today with rotating machinery. In this area, the vast amounts of collected data and operating experience have made it possible to empirically relate certain modal changes to specific types of failure in rotating machinery.

In the area of offshore platforms, a significant amount of research has been done in the last five years to detect and locate failure via measured vibration data. There have been several studies in which platforms were first mathematically modeled and then systematically weakened (by removing a particular member, for example), and the changes in the modal parameters were recorded. In this way, a backlog of "simulated experience" can be acquired that permits the interpretation of modal changes with regard to structural integrity. Similar experiments on scale models have also been reported. This research indicates that the results are site specific and that their interpretation requires both expert or experienced judgment as well as a good knowledge of the particular structure. Nonetheless, this seems to be a promising approach, and similar research should be conducted on nuclear power plant structures.

RECOMMENDATIONS

The following recommendations are made:

- Past research has helped to characterize the nonlinear behavior of nuclear power plant structures, especially the dependence of damping on excitation level. However, if suitable data are generally unavailable, additional tests should be carefully planned and data collected systematically so that additional studies into nonlinear behavior can be performed.
- Research indicates that there is a clear relationship between changes in structural integrity and shifts in the modal parameters of a structure. Additional research is still needed to extend the promising results obtained for rotating machinery and offshore platforms to nuclear power plant structures. Since modal shifts can be detected at low excitation levels, it may be possible to use various ambient excitation forces (e.g., wind, fluid, seismic, machinery). Therefore, we strongly urge that experiments be conducted to monitor modal parameters of nuclear power plant structures that are excited by these ambient forces to determine the quality of the data that can be obtained. As a backup, we also recommend a simultaneous investigation into simple, economical in-situ excitation techniques that would permit modal analyses to be easily and routinely performed. The sensitivity of the modal parameters to changes in the structural integrity is usually determined empirically by examining large quantities of data from structures that have been damaged. It is, therefore, recommended that a data collection and modal parameter monitoring program be conducted at several nuclear power plants to build up a base of historical data from which modal parameter changes can be related to actual failure or damage. This data collection program would be greatly facilitated by the previously mentioned search for ambient or simple in-situ excitation techniques. It is also recommended that such sensitivity studies be conducted using simulated data from analytical models and experimental data from scale-model structures.

- It appears that model modification codes are best suited to study nonlinear structures. To date, no such code has been analytically qualified for use on nuclear power plants. Consequently, we recommend that a program be initiated to qualify a model modification code in the same fashion that the PARET modal analysis codes were qualified.

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APPENDIX A:
DETECTION OF DAMAGE IN STRUCTURES

Appendix A is a fiche copy of Ref. 1, a report prepared by Structural Measurement Systems, Inc. The report appears in its entirety on fiche 1 through 3 in the pocket attached to the inside of the back cover of this report. For convenience in locating pertinent sections, the contents pages and an unedited excerpt from the report's introduction are printed as the remainder of this Appendix.

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1.1 OBJECTIVES OF THE STUDY

The stated object of this study was to survey the technical literature and interview selected experts in the fields of dynamic testing and analysis to determine the state-of-the-art of the relationship between physical damage to a structure and changes in its dynamic (modal) properties.

During the course of this study we took a broad look at the problem of relating physical damage to changes in modes of vibration. We did not attempt to discover specific schemes for detecting damage. Instead we concentrated on three major areas of investigation related to this problem. They are:

1. A tutorial treatment of modal analysis.
2. Modal testing methods.
3. Analytical/experimental studies related to the verification of the relationship between physical damage in a structure and changes in its modes of vibration.

The first topic we chose, in agreement with our contract monitor, out of a need we felt to clearly state the modal analysis theory as it relates to vibration measurements. There is a multitude of terminology associated with the structural dynamics field, and structural engineers, depending upon the industry in which they work (e.g. aerospace, automotive, nuclear, heavy construction, or otherwise) and the methods they commonly use describe the same concepts in different terms. Furthermore, the majority of literature on modal theory is contributed by dynamicists who work with computer based dynamic models (finite element models) and have little or no contact with measurements. In short, we have included in this report a consistent presentation of the concept of a mode of vibration and explained many of the

terms and assumptions surrounding the use of modal analysis to characterize the dynamics of structures.

The second topic of this report, namely, testing and data analysis methods, is an area where we collected a large amount of information. With the advent of mini and micro computers, and the implementation of efficient computational algorithms such as the FFT (Fast Fourier Transform) in these small machines, many new testing and data processing methods have sprung up during the past 5 to 10 year period. Emphasis is placed on these newer digitally based methods in this report because they appear to hold more promise for the future.

Lastly, the topic most germane to this study, that is, experimental or analytical evidence of the relationship between physical damage and changes in modal properties, yielded some very significant results. This material was further subdivided into four major areas because the vast majority of the literature surveyed fell into one of these categories. The four areas we chose are:

1. Nuclear Power Plants
2. Large Structures
3. Rotating Machinery
4. Offshore Platforms

Our findings are presented in this report primarily in the form of quotations of the results, conclusions and recommendations of the researchers whom we interviewed.

At the end of this report we include a bibliography of the literature which we reviewed. This is by no means an exhaustive list of literature on this subject. However, many of the references listed here contain excellent lists of additional references which will take the interested reader back through the history of experiences of the author(s) of that particular paper.

In 1973 D. R. Houser & M. J. Drosjack wrote a very comprehensive report (Ref. G.43) on vibration signal analysis techniques, which discusses integrity monitoring from a broader perspective than is covered in this report. They do not limit their discussion to the use of modal parameters as the primary discriminants for detecting structural damage as we do here.

APPENDIX B:
EXPERIMENTAL SEISMIC EVALUATION OF NUCLEAR POWER PLANTS

Appendix B is a fiche copy of Ref. 2, a report prepared by ANCO Engineers, Inc. The report appears in its entirety on fiche 4 and 5 in the pocket attached to the inside of the back cover of this report. For convenience in locating pertinent sections, the contents page and unedited abstract and executive summary are printed as the remainder of this Appendix.

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1.0 ABSTRACT

This study reviews experimental techniques, instrumentation requirements, safety considerations, and benefits of performing vibration tests on nuclear power plant containments and internal components. The emphasis is on testing to improve seismic structural models. Techniques for identification of resonant frequencies, damping, and mode shapes, are discussed. The benefits of testing with regard to increased damping and more accurate computer models are outlined. A test plan, schedule and budget are presented for a typical PWR nuclear power plant.

2.0 EXECUTIVE SUMMARY

The goal of this study is to describe the technical and cost factors relevant to a decision on whether or not to use testing to verify and improve on the dynamic analysis and theoretical models of nuclear power plant containment buildings and internal equipment. Vibration tests at nuclear power plants have been conducted at over 30 sites and have provided valuable information on design adequacy, have demonstrated higher damping than allowed by regulatory standards, and have usually demonstrated increased seismic capacity of the tested facility. The techniques and justifications for such testing have been fully developed over the last ten years.

Vibration tests at the San Onofre Nuclear Generating Station (SONGS) were first conducted in 1969, following preliminary tests on several prototype and research reactor facilities. These tests concentrated on the containment structure and the primary coolant loop. The importance of soil-structure interaction was demonstrated as well as the presence of high damping (~18 percent) in the lower modes of vibration even at low (10^{-3} g) acceleration response. The studies on the coolant loops led to improved mathematical models and structural modifications to achieve greater seismic capacity. Vibration tests were more recently (1978) carried out on the Diablo Canyon Nuclear Power Plant in order to demonstrate greater damping and seismic capacity of equipment and piping systems. These data were helpful in establishing the adequacy of the plant in view of increased seismic design requirements (0.4 g to 0.75 g). Earlier vibration tests on other containments (such as SONGS) and the demonstrated high values of damping were used to justify higher values of damping (7 percent) at Diablo Canyon. An extended research program sponsored by the Federal Republic of Germany at the HDR nuclear plant near Frankfurt is providing information on the moderate-to-high level response of containment structures (10^{-3} to 10^{-1} g) and piping systems (10^{-1} to 10^1 g). Damping of 5 percent was found at moderate levels of containment response. High level tests are scheduled for October 1979. Tests on one-twelfth scale containment models, sponsored by

EPRI, have been conducted to scaled accelerations of 0.3 g using buried explosives and eccentric mass shakers. The results indicate very high values of damping (10 to 20 percent) and the importance of nonlinear soil-structure interaction. Other test programs support these observations and are discussed in the report.

A variety of testing methods are available for exciting containment structures to any reasonably desired levels of response (10^{-1} to 10^0 g). The most promising and field proven are eccentric mass sinusoidal vibrators (with forces up to 10^6 lb) and the use of buried explosives (using up to several tons of explosives). Linear hydraulic actuators, impulsive shear rams, and rockets are also potentially useful, but have not been as fully proven out. Equipment can be tested by the above methods and also with snapback techniques, electromechanical vibrators, and the base motion caused by exciting the containment itself. If only equipment is to be tested, direct excitation of the equipment is preferable to containment excitation. Instrumentation for such testing is readily available. Data gathering, accuracy, and presentation are greatly enhanced by recent developments in computerized vibration analysis systems and portable real-time spectrum analyzers. The exact choice of testing method depends on the specific plant tested, soil conditions, surrounding buildings, goals of the project and other factors.

A more severe restriction than attainable levels of response in testing is the *allowable* level of response. Test programs on operational facilities must avoid amplitudes which could produce adverse regulatory effects (or other measure of "damage"). In conflict with this requirement is the desire to test to the highest response levels acceptable to demonstrate the maximum* damping possible and to investigate other nonlinear trends. ANCO test programs have, for example, lead to reductions in predicted seismic response by factors of 1.2 to greater than 2 (15 percent to 50 percent less response), depending upon system design, materials, erection, and boundary conditions.

*Energy dissipation is typically amplitude dependent and has been observed to almost always increase significantly with test response level.

These reductions have been the product of nonlinearities as well as conservative design criteria applied to even low level response.

Herein it is argued that concern for equipment is a more restrictive test response requirement than concern for containment structures. In plants designed for low seismic areas, the authors feel that containment responses on the order of 50 to 100 percent of that to be generated by the predicted Operating Basis Earthquake (OBE) motion* are acceptable during testing. Plants designed for higher seismic inputs may be more strictly limited to a smaller fraction of their OBE due to concern for seismic Class III equipment. In any case the allowable levels of response appear to be greater than those required to demonstrate the validity of models and provide higher damping estimates.

A test program will typically involve measurement of damping values, resonant frequencies, and mode shapes. The variations in these properties with level of response is useful to the understanding of nonlinear properties. Parameter identification techniques can be used in the field or after the test to estimate these dynamic properties from response data. Other techniques, such as Bayesian identification, are useful to modify models or parameters of models (such as soil properties) in order to more closely match the identified system dynamic properties. These techniques have been fully demonstrated on a variety of structures including those from the aerospace industry as well as nuclear power plant structures and equipment.

Testing costs will vary considerably depending on the scope and goals of the test. Simple tests to estimate a few resonant frequencies and dampings on an uncomplicated piece of equipment can be carried out for less than five thousand dollars. Extensive research efforts involving both theoretical and experimental investigation on a containment and its internal equipment can cost well over a million dollars. Generally, the test program can be scoped such that the economic benefit of reduced down-time is several times the cost of testing. A procedure for test planning, budgeting, and scheduling and an example test are presented later in this study.

*OBE free-field maximum accelerations are typically 0.1 g - 0.2 g at most U.S. sites.

APPENDIX C:
VERIFYING SEISMIC DESIGN OF NUCLEAR REACTORS BY TESTING

Appendix C is a fiche copy of Ref. 3, a two-volume report prepared by Agbabian Associates. The report appears in its entirety on fiche 6 and 7 in the pocket attached to the inside of the back cover of this report. For convenience in locating pertinent sections, the contents pages and unedited executive summary of volume 1 are printed as the remainder of this Appendix.

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EXECUTIVE SUMMARY

This report establishes a program plan for nuclear power reactor managers to verify that their facilities can weather a safe shutdown earthquake.

Management will find that the plan approaches the verification problem from a somewhat different point of view than has been the custom. It draws upon the work that has been traditionally applied in the nuclear reactor industry. In addition, because of the long-term experience that the authors have had in verifying the survivability of military systems to ground shock caused by high-explosive and nuclear weapons, it is felt that the plan has been improved by incorporating some of these concepts. In having worked on both civil and military systems, from both an analytical and experimental point of view, we detect that real improvement can be made in existing procedures.

The program plan will be practical and significant if it fulfills three functions: (1) it provides a basis for more accurate verification, (2) it reduces the uncertainties of the verification assessments, and (3) it is economically feasible. We have been guided by these three principles.

The test plan is first and foremost predicated on the knowledge that at least some elements of a reactor facility will respond nonlinearly when subjected to a major earthquake. That being the case, we believe that the testing techniques should incorporate a means for subjecting the facilities to earthquake-like motions at amplitudes as high as the utility manager is willing to tolerate. This approach is recommended because failure, damage, and low-cycle fatigue of structures and equipments are definitely related to actual earthquake signatures and not to so-called simpler equivalent sine-type or other steady-state excitations.

On the other hand, these steady-state measurement techniques can be of significant value. If elements of the facilities do respond linearly, those techniques provide an excellent means for performing modal analyses or otherwise exciting responses that can be directly extrapolated to full earthquake levels. As importantly, they can be used as diagnostic tools to help identify and quantify damping and other physical characteristics of facility response to aid in the development and use of mathematical models.

Unquestionably, when high-level tests that produce earthquake-like motions are used, they will be limited to how much shaking can actually be applied to an operational reactor. Whatever that limit, the structure and equipment response data must be projected to the safe shutdown earthquake level using mathematical models. The higher the level of shaking applied to the structure by test, the less will be the uncertainty when the results are extrapolated to full earthquake levels. This plan addresses how such extrapolations should be made, and discusses at some length the need for secondary tests that identify and characterize nonlinear behavior and establishes procedures that will aid in keeping the uncertainties of extrapolated responses within acceptable bounds.

The most comprehensive and reliable means for creating earthquake-like responses of reactor structures, subsystems, and equipments can be accomplished with high-explosive tests. Charges buried in the free-field medium are arranged to produce the desired motions of the structures. They are detonated in a sequence that is determined from optimization routines described in this report.

When the high-explosive method cannot be used or where an adjunct testing technique is desired, pulser-type tests are recommended. Pulsers are devices that are mounted directly to structures or equipments to produce earthquake-like responses of those elements. Briefly, these devices have as their source of energy, compressed gas, superheated steam, or chemical charges. The devices are arranged on the structure in arrays that are initiated

according to schedules that are determined from computer-aided routines also described in this report. The program recommends tests that can be conducted within the framework of an operating facility. In other words, reactor shutdown is not required although, of course, it simplifies the procedure and possibly means that tests could be conducted at a higher level of excitation.

The reactor facility responses produced by either high explosives or pulsers are to be correlated directly to the responses predicted from mathematical models. Via computer-based optimization routines described in this report, the parameters of the mathematical models are varied until an acceptable agreement is achieved between the experimental data and the analytical data. This process is called the validation phase. When the mathematical models have been validated, they are subsequently used to predict the reactor facility response to full earthquake motions. This is the verification process. The report details how the validation and verification processes are to be accomplished. In so doing, the reactor plant manager and his representatives will also be guided in the selection and implementation of the preferred mathematical models that should be used.

The procedures by which tests are to be planned for specific sites are covered in this report. In the process, instrumentation and measurement systems must be selected, and guidance is given for this choice. Data obtained from the tests must be processed in specific ways and the appendix directs its attention to this important subject.

Finally, the reactor plant manager will be interested in the cost of a typical verification program and the elapsed time and on-site time that will be required. This report provides guidance for estimating detailed site specific costs and schedules. In addition, an approximate nonspecific site estimate of costs and time has been made for a high-explosive-test program. These data are presented in the accompanying table as a range of values. They should be used for guidance only. Specific site conditions and management decisions will affect these estimates. No attempt has been made to estimate cost and schedule figures for pulser tests because the specific design of the facilities controls the design of such testing systems.

PRELIMINARY COST AND SCHEDULE ESTIMATE IN PERFORMING HIGH-EXPLOSIVE TESTS

Cost Estimate, Dollars		Project Duration, Months		On-Site Time, Months	
Low Range	High Range	Low Range	High Range	Low Range	high Range
300,000	900,000	9	14	4	6

APPENDIX D:
ANALYTICAL QUALIFICATION OF SYSTEM IDENTIFICATION CODES

Appendix D is a fiche copy of Ref. 7, a report prepared by the author and his colleagues at LLL. The report appears in its entirety on fiche 8 in the pocket attached to the inside of the back cover of this report. The report's abstract is printed as the remainder of this Appendix.

I ABSTRACT

In this report we describe the analytical evaluation of two particular system identification codes used at Lawrence Livermore Laboratory. Both codes are eigenparameter identification codes, however, one uses a time domain approach while the other a frequency domain approach. The evaluation was accomplished by analytically generating several time history signals in which the true modal parameters were known. These time histories ranged from widely spaced modes with spacing factors* of 100 percent to closely spaced modes with spacing factors of 6 percent. These signals were then polluted with various levels of simulated measurement noise and the ability of our computer codes to extract the parameters from this noisy data was evaluated. We were unable to detect any substantial difference in the performance between the time domain and frequency domain approach. We also found that the performance of the codes was not a function of the modal spacing (at least down to a spacing factor of 6 percent). Finally we found that performance of the codes was clearly a function of the signal to noise ratio.