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Verifying Seismic Design of Nuclear Reactors by Testing

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Lawrence Livermore Laboratory

Agbabian Associates

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ABSTRACT

The purpose of the study is to develop a program plan to provide assurance by physical demonstration that nuclear power plants are earthquake resistant and to allow nuclear power plant operators to (1) decide whether tests should be conducted on their facilities, (2) specify the tests that should be performed, and (3) estimate the cost of the effort to complete the recommended test program.

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

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PREFACE

This report was prepared by Agbabian Associates (AA) under Purchase Order No. 5190709 for the Lawrence Livermore Laboratory (LLL) at Livermore, California. The objective of the work is to develop a program plan to provide assurance by physical demonstration that nuclear power plants are earthquake resistant and to allow nuclear power plant operators to (1) decide whether tests should be conducted on their facilities, (2) specify the tests that should be performed, and (3) estimate the cost of the effort to complete the recommended test program.

The report is a collective effort of B. Barclay, J.A. Malthan, S.F. Masri, and F.B. Safford at AA who developed the plan. They were assisted by J.W. Athey for editorial organization, and C.S. Becker who typed seemingly endless revisions to the report.

The support of R. Murray and J. Weaver of Lawrence Livermore Laboratories is greatly acknowledged. Special thanks is given to D. Arthur at LLL for his great interest and guidance in this project and for his very helpful review comments of the report draft.

SECTION 1

INTRODUCTION

This document sets forth Agbabian Associates' (AA) recommendations for a verification program to test the ability of operational nuclear power plants to achieve safe shutdown immediately following a safe-shutdown earthquake.

The study described in this report is part of the Lawrence Livermore Laboratory (LLL) Parametric Estimation Techniques (PARET) program. PARET is a Nuclear Regulatory Commission (NRC) funded program concerned with the application of system identification techniques to nuclear power plant structures and equipment. The PARET program is now focused primarily on the earthquake response of nuclear plants.

1.1 PURPOSE

The purpose of the study is to develop a program plan to provide assurance by physical demonstration that nuclear power plants are earthquake resistant and to allow nuclear power plant operators to (1) decide whether tests should be conducted on their facilities, (2) specify the tests that should be performed, and (3) estimate the cost of the effort to complete the recommended test program.

1.2 SCOPE

It is envisioned that the management of nuclear power plants will establish the level of safety of their plants at Safe Shutdown Earthquake (SSE) levels through analytical investigations. This is the verification process. The study reported herein describes a series of experimental investigations that would serve to define the parameters to be used in seismic analyses of nuclear power plant structures and critical equipments. Better definition of such parameters may be expected to enhance the reliability of the analytical investigations. This process is termed validation.

The improvement of analytical techniques to yield more reliable conclusions about power plant performance is not included in the scope of this study. However, the study does comment on the viability of certain analytical procedures with an eye toward establishing the relationship between test and analyses toward maintaining a well balanced program. Moreover, analytical techniques are discussed to the extent necessary to clarify the underlying assumptions of the tests and to explain the interpretation and use of test data.

The tests herein encompass primarily innovative procedures that are not widely practiced at this time. They are recommended because they are expected to markedly enhance the quality of verification and to reduce and quantify uncertainties in the verification process. This study is intended to explore ideas which could have attractive payoffs to plant managers who desire to more fully understand and evaluate the seismic safety margin of their nuclear power plants.

1.3 REPORT ORGANIZATION

This report has been organized into two volumes. Volume I is the Test Plan and Volume II is the appendix, titled Theoretical Discussions.

Volume I has been organized and presented for the nuclear power reactor manager on the one hand and his support staff on the other. The early sections present a fairly straightforward statement of the verification problems and the attendant recommended solutions to those problems. As the reader penetrates further into the report, these ideas are expanded and necessarily become more complex and interrelated ultimately leading to detailed procedures that are necessary to the implementation of the test plan.

Thus, if the reader merely reads the executive summary, he will have obtained a grasp of the plan. If in addition he also reviews Section 1, the Introduction, and Section 2, the Overview of the Test Program, he will have seen at least a part of the rationale of the approach.

Section 3, Test Design Philosophy, presents a discussion of the tests recommended in the plan together with a review of the technical problems that will be encountered in any verification effort. A general review of the testing techniques that have been applied to nuclear reactor facilities, or to military systems, are covered in Section 4, Test Input Excitation Sources. This section also presents a description of the test configurations and test hardware that are to be used.

A detailed description of the procedures to be implemented for the design and implementation of the various tests of the program is presented in Section 5. These procedures also relate the acquired test data to the analytical procedures that will be necessary to arrive at a verification statement of reactor facilities.

Section 6, Test Planning, presents guidelines for preparing detailed plans for performing tests at each reactor facility. On a related subject, the description and selection of instrumentation and measurement systems applicable to the test plans are covered in Section 7, Procedure for Selecting Instrumentation and Measurement Systems.

Finally, Section 8, Procedures for Scheduling and Cost Determination, recommends a procedure for arriving at detailed cost estimates and elapsed time for the verification of a reactor facility. In addition, a range of cost estimates and elapsed times have been presented to provide a utility manager with some idea of the scope of effort for the tests recommended in this plan.

Volume II, Appendix--Theoretical Discussions, presents backup technical information that supports the procedures delineated in Volume I.

SECTION 2

OVERVIEW OF THE TEST PROGRAM

The test program presented in this report is designed to expose nuclear reactor facilities to earthquake-like motions for the purpose of validating mathematical models that ultimately are used to verify the safety of structures, equipments, and subsystems. The recommended tests include: (1) high explosive (HE) field tests, (2) pulser tests applied to major structures, and (3) pulser tests applied to equipments and subsystems. These three major tests are supported by diagnostic tests that are intended to reveal behavioral characteristics of the facilities so that more accurate response predictions may be made.

The HE tests comprise buried charges in the soil or rock immediately surrounding the nuclear reactor. These HE charges can excite massive structures, their foundations, and associated equipments to magnitudes that approach a safe shutdown earthquake (SSE). Realistically, it is recognized that motions of this magnitude cannot be tolerated in operational facilities. Accordingly, the charge weights will be reduced to produce an acceptable level of motions. The program then devises a means for extrapolating these data to full earthquake levels.

The pulser tests described in this report require various relatively small but high energy output devices that are attached directly to structures or equipments. Pulsers use mechanical, pneumatic, chemical, or other means to produce transient forces that can excite a range of small equipments or large major structures to earthquake-like motions, although at magnitudes lower than can be achieved in HE tests. This is accomplished by assembling the pulsers in arrays, where required, to produce the requisite motions. Again, the facility responses must be extrapolated to the SSE level by techniques delineated in this report.

The planning and conduct of these tests and the utilization of test data occurs in four phases.

Phase I: Develop the motions that the structures would experience in an SSE event.

Phase II: Design the high explosive or pulser arrays to generate a sublevel of the Phase I environment.

Phase III: Conduct tests and perform a validation of the analytical techniques that are eventually used to verify the reactor facilities.

Phase IV: Perform the verification studies from the validated models of Phase III and prepare a test and verification report.

The phases are briefly described in this section, with respect to their applications to the three classes of tests. Phases I, III, and IV are similar for all three types of tests, while the application of Phase II varies according to the type of test being applied. A detailed discussion of each phase is given in Section 5, supported by discussions of the variables requiring consideration in Section 3. The actual hardware and test configurations are covered in Section 4.

2.1 PHASE I: CONVERSION OF FREE-FIELD CRITERION SPECTRA TO FREE-FIELD MOTION

The purpose of Phase I is to develop and implement a procedure for converting specified criteria earthquake spectra to free-field motions suitable for performing subsequent linear and nonlinear analyses of reactor structures and equipments.

2.2 PHASE II: DESIGN OF ARRAYS TO EXCITE STRUCTURES AND EQUIPMENTS

Based on the free-field motions determined in Phase I, the motions of the foundations of the reactor structures will be determined by mathematical models that accurately represent the interaction between the free-field medium and the structures.

If high-explosive tests are to be conducted, arrays of buried charges will be designed so that the predicted foundation motion can be actually reproduced.

If pulser tests are to be applied to the superstructures of the various reactor structures, additional calculations will be required to predict the superstructure motion based on the previously calculated foundation motion. Thereafter, arrays of pulsers will be designed to be applied to the superstructures to produce those predicted motions.

If pulser tests are to be applied to equipments or subsystems, mathematical models will be used to predict the motions of the equipments or subsystems at their attach points to the parent structure. Thereafter, pulser arrays will be designed to be attached at the interconnect points of the equipment or subsystems and the parent support structure to produce those predicted motions.

The manner in which the high-explosive arrays or pulser arrays are selected is based on computer-aided optimization routines. These routines essentially search for the energy release characteristics, physcial spacing, and sequencing schedules of the high-explosive charges or pulser outputs to cause the structures to respond in their prescribed motions.

2.3 PHASE III: VALIDATION OF MATHEMATICAL MODELS

The high explosive and pulser arrays designed in Phase II are implemented in Phase III to subject the reactor structures and equipments to earthquake-like motions.

These motions are to be compared to predictions of structure and equipment or subsystem responses in order to determine the accuracy of the mathematical models. Generally, the mathematical models used in this phase are the same as those used in Phase II to design the high explosive or pulser arrays. In Phase III, the parameters of the models are iterated until the predicted responses acceptably match the measurements obtained from the tests. The parameter selections that include representations of stiffness, mass, damping, strength, and post yielding behavior are determined from computer-aided routines which systematically search for the matrix of parameters that minimizes the differences between the prediction and the measurements.

In the process of selecting the parameters, the general adequacy of the formulation of the mathematical models is also investigated. Recommendations for upgrading the models then become a fallout of this investigation. Because the tests are performed at sub-SSE levels, projections of the behavior of the parameters at response levels commensurate with the SSE are then made. The projections or extrapolations are aided by small-scale on-site diagnostic tests that are conducted to ascertain the behavior of reactor structures and equipments at the elevated stress levels associated with the SSE.

In some cases, where structures, equipments, or subsystems respond linearly, the HE or pulser test data can be scaled directly up to the SSE level to obtain an immediate assessment of reactor facility response. In these cases, parameter optimizations are not required and the verification of Phase IV can be performed without further data manipulation.

2.4 PHASE IV: VERIFICATION OF REACTOR FACILITIES

The validated mathematical models developed in Phase III and the projected parameter values are finally used to predict the response of the reactor structures, equipments, and subsystems to the full SSE level. Subsequently, these full-scale calculations are studied to assess the adequacy of the reactor facilities. Probable failure modes (if any) are identified and redesign recommendations are made. The data, conclusions, and recommendations are ultimately presented in a final assessment report.

SECTION 3

TEST DESIGN PHILOSOPHY

Several important considerations influence the types of tests that can be conducted on nuclear power plant structures and equipments. This testing will be accomplished using a level of excitation lower than an SSE event because safety requirements will not allow testing at high amplitude levels. Thus, even though large amplitude tests could be performed, the level that will be allowed will display the important hallmarks of a natural seismic event. The test plan then establishes a procedure to project or extrapolate the test results to an SSE level as part of the verification process. To do this, a basis for extrapolating system parameters obtained at one level must be made relevant to those at a higher level. This methodology is described in detail in Section 5, along with the general methodology of the program plan. The present section describes two main classes of excitation for testing and the factors that influence the determination of parameters: nonlinearity, damping and site-dependent factors. The means of supplying the exciting force are considered later, in Section 4.

3.1 ROLE OF TESTS

The ability of nuclear power plant facilities to survive an SSE can be verified through analytical investigations. The principal objective of investigative tests is to determine system parameters (e.g., mass, stiffness, strength, damping, or other functional characteristics) that can be used in the validation of mathematical models representing the facilities. Although it is considered impractical to test structures at the SSE level, results from reduced level tests can be extrapolated to yield parameter values at SSE levels. To aid in this extrapolation, diagnostic tests are conducted at more than one excitation level to discern trends in parameter values. Because the structural system and some equipments will behave nonlinearly when shaken by an SSE, the best testing estimates will include system characteristics under prevailing nonlinearities. Proof-testing of individual components may be helpful and occasionally applicable, although this technique for the entire structure, or even for extensive subsystems of the facilities, at the SSE level is generally impractical.

3.2 BASIC TYPES OF EXCITATION

Dynamic testing of structures and equipments is performed using several methods of excitation. For in-place testing, two classes of tests are applied: dynamic system characteristics tests and earthquake simulation tests. Laboratory testing of equipment is feasible only when the equipment can be readily transported to the laboratory.

Two general types of tests that can be applied to structures and equipments are so called steady-state (or stationary) tests and transient tests. Steady-state tests consist of (1) slow sine sweeps, and (2) sine dwells (Mustain, 1976). Transient tests include (1) fast sine sweeps (chirp tests), (2) random, (3) various forms of impulsive loads, and (4) nonstationary (earthquake-like) random excitations (Otnes et al., 1972).

3.2.1 DYNAMIC SYSTEM CHARACTERISTIC TESTS

If systems respond linearly at all excitations levels, steady-state techniques can determine mode shapes, modal frequencies, and damping. If nonlinear behavior occurs in the structure and equipment, the steady-state technique must yield to one of the transient methods suitable for nonlinear systems. Transient tests can determine modal properties of linear structures/equipments, while also lending themselves to transfer functions. The transfer function approach provides the basis for making immediate response predictions without resorting to modal decomposition or synthesis. By applying transient pulses at increasingly larger amplitudes, a measure of the nonlinear response of the structure and equipment may be estimated.

3.2.2 EARTHQUAKE SIMULATION TESTS

An important consideration in testing for earthquake simulation is the wave shape, i.e., the precise details of the time history of the input transient. In general, the response time history of a test article under a simulation test should show a reasonable approximation to the response it would see in an SSE. Failure, damage, and low-cycle fatigue of structural elements are directly related to the amplitude time histories of the structure (Fackler, 1972). Equipment malfunctions and damage are also directly related to the response characteristics (Safford et al., 1974a). Standard impact tests, sine beat, slow sine sweep, and dwell tests demand an equivalence to the actual earthquake response which introduces an additional complexity and uncertainty in the verification process.

To date, in-place testing of nuclear power plant structures has generally used excitation that is designed to match a scaled version of the shock response spectrum or equivalent (Chrostowski et al., 1972). It is important to realize that widely divergent time histories can be compatible with given response spectra. Therefore, in order to adequately simulate seismic response, the input excitation must not only match a specified response spectrum but it must have a time history that closely resembles earthquake ground motion in total duration, amplitude, and general waveshape.

A major feature of the testing program proposed herein for earthquake motion simulation is the use of optimization routines capable of generating input pulses that will produce a desired time-history response in a power plant or on equipment (Masri et al., 1976). Specifically, a suitably scaled version of a specified shock response spectrum will first be used to generate a time history of motion at one or more specified locations in the structure. Next, the optimization technique referred to above will be used to synthesize the pulse time histories that must be applied to generate the desired response. Finally, the energy source that provides the excitation will be configured to deliver input pulses which will excite the structure or equipments, multiaxially, and which approximates a sub-SSE seismic event.

3.3 TYPES OF TESTING

Conceptually, the complete testing of a nuclear power plant system comprises three types of testing. In the first, the entire facility (or critical portion of a facility associated with safe shutdown) is subjected to a high-explosive-induced ground motion with the characteristics of an earthquake at as high levels of excitation as are prudent. Such a test would most closely simulate a true seismic event, and the observed response would include the effects of site/medium and structure/equipment interaction.

In the second type of testing, excitation would be applied directly to the structure. The response would therefore include structure/equipment interaction, but the test would not directly simulate site/medium interaction (Safford, 1978). This type of testing may replace the first type when, for any reason, direct excitation of ground motion is not feasible. Alternatively, the second type of testing may serve as a supplementary test to provide additional data on the response of internal equipment.

The third type of testing concerns the excitation of specific internal equipments. Such tests may be performed by local excitation of a limited region of a building or by subjecting in-place equipment to directly applied dynamic tests (Saffort et al., 1977). Again, these tests provide an earthquake-like excitation.

A diagnostic type test which has the capacity to locally excite a structure or equipment to produce stress levels comparable to actual earthquake conditions is also desirable. These tests are not necessarily required to provide an earthquake-like motion. Such tests provide a basis for ascertaining the type of nonlinearities in a system and for quantifying these data (Safford et al., 1971). Typically, such information is used to develop linear or nonlinear models to perform verification studies. Their importance cannot be overemphasized and they are highly desirable if the transition from the validation phase to the verification phase is to be accomplished with a high degree of certainty.

3.4 NONLINEARITIES

Nonlinearities that influence the response of a nuclear power plant arise from several sources:

1. The earth medium through which the earthquake ground motion must propagate before reaching the structure
2. Inelastic behavior of structural components at high levels of excitation (material nonlinearities)
3. The action of snubbers when large displacements occur at high levels of excitation (geometric nonlinearities)
4. Stress response of other nonlinear equipments and subsystems resulting in an interaction effect between parent structures and equipments acting like an energy absorber.

The presence of the nonlinearities means that system parameters vary with the imposed stress level. The excitation levels in most test programs will be below SSE levels. Therefore, the system parameters determined from test must be extrapolated to SSE levels. The procedures of extrapolation are given careful consideration in this document.

One feature of the proposed tests involving direct excitation of ground motion is that site/structure interaction (SSI) is present and therefore the nonlinear aspects of response due to earth material behavior are brought into play. Commensurate with safety, the anticipated test levels could be optimized to induce inelastic structural behavior and/or bring snubbers into action. If safety requirements preclude testing at such high excitation levels, the mathematical models must carry a large burden of the verification. In this case, it is useful to employ local diagnostic tests to affirm the system behavior at elevated levels of excitation.

3.5 DAMPING

Of the parameters affecting the dynamic response of a structural system, damping is usually the least understood and the most difficult to determine. The damping parameter used in analysis must include the combined effects of a multitude of energy dissipation mechanisms. In a nuclear power plant structural system, such mechanisms include inelastic behavior of structural components, action of snubbers, dissipation at structural and structure/equipment connections, and possible energy losses occurring in the earth medium.

Current practice in the dynamic analysis of nuclear power plant structures dictates a damping coefficient of approximately 5%. There is widespread belief that the actual damping at SSE levels is considerably higher. However, there is also a common contention that tests will not substantiate the above hypothesis because the feasible excitation levels are too low to mobilize the inelastic behavior and snubber action that would potentially provide high damping at SSE levels. However, this study suggests a diagnostic test technique that determines local damping and nonlinear response mechanisms at the point where local test loads can be applied. The procedure is discussed more fully in Section 5.

3.6 SITE-DEPENDENT FACTORS

Observed seismic ground motions often exhibit noticeable differences depending on the depth of soil above bedrock at a given site. Since nuclear power plants are located in a wide variety of geological sites, the test program must address site-dependent factors in designing the test input. Specifically, the configuration of the energy source providing the input excitation must take into account the special needs dictated by the given site.

As described in Section 2, a promising method of exciting ground motion is the use of high explosive (HE) tests. Such a test would use one or more arrays of HE charges buried in the vicinity of the nuclear power plant structure. A major consideration in an HE test is the suppression of high frequency that is not characteristic of pure seismic motion. At sites where there are deep soil deposits, the soil can be expected to absorb much of the high frequency motion. As a result, the motion close to the structure may approach seismic ground motion in its frequency content. However, at sites where bedrock is close to the surface, less absorption of high frequency components is to be expected, although this would depend on the extent of jointing in the rock. In such cases, special measures have to be adopted to modify the basic frequency content of the explosive pulse.

A method of solving this problem has been reported in Abrahamson (1979). In this approach, the burst is contained within a rubber bladder that extends the duration of the blast pulse and eliminates some of the high frequency components of the explosion. Variants of this technique may be required in the proposed tests to manipulate the frequency content of the input pulse as desired, especially at sites where the bedrock is so close to the surface that the HE charges may be embedded in the rock.

SECTION 4

TEST INPUT EXCITATION SOURCES

This section presents technical discussions of the test methods recommended for the verification of nuclear reactor structures and equipments. It should be acknowledged at the outset that some elements of the recommended program have not previously been applied to nuclear reactor facilities. Indeed, the program is eclectic in that it draws upon various sources of information and selects test techniques from other disciplines to achieve a plan that is tailored to satisfy the intent of the verification program.

The principal sources of energy recommended in this program for testing reactor facilities produce impulsive-type loads. Specifically, high explosives are seen as the most comprehensive method for exciting structures and equipments in the modes of response that they would actually experience in an earthquake. Alternatively, pulser techniques applied to the structures directly or to equipments (either in place or removed off site) add a dimension that supplements or replaces high-explosive techniques. In addition, smaller, more conventional excitation methods are seen as an approach for revealing the behavior of systems throughout their range of response up to and including full SSE levels encompassing both linear and nonlinear behaviors.

Historically, modal measurements have been made on structures using rotating eccentric shakers for slow sine sweep and sine wave dwell. Some of the earliest studies were performed by Prof. Lydik Jacobsen, Stanford University, on campus buildings and on the Hoover Dam in the early 1930's. These procedures have been fully developed over the years and are in widespread use at this time. However, application of sine wave vibrators to complicated structures with closely spaced modes has proved to be difficult and has necessitated the use of multiple shakers (six or more in some cases) to adequately isolate pure modes. Modern techniques, which consist of broadband excitation, digital signal capture, and efficient computer algorithms, are rapidly predominating and supplanting this older method.

The most commonly used force-function generators are electrodynamic and electrohydraulic shakers that produce continuous periodic (usually sinusoidal) functions that are controllable in amplitude, time duration, and frequency. With sophisticated control systems, these devices are also capable of generating random and complex force functions (chirp) as well as simple pulses. Higher capacity electrohydraulic shakers can produce up to 50,000 lbf.

Rotating eccentric mass shakers for slow sine wave and resonance dwell exist in several universities, government laboratories, and private corporations. Capacity of output forces vary up to 100,000 lbf.

Shock machines, impact hammers, pulse train generators, and explosives produce a second family of implosive or transient driving functions. These types of functions may include many pulses of varying forms (e.g., half-sine, triangle, square), depending on the required input. Important considerations with these devices are the generation of continuous functions in the frequency bandwidth of interest and adequate motion generation in the structure for favorable signal-to-noise ratios.

The use of high explosives to test structures has precedence in past efforts to a very large extent on military facilities, and to a limited extent on nuclear reactors. However, the manner in which the explosive charges are configured and the specific objectives of the plan are new. The result is a test procedure that will produce more realistic earthquake motions for shaking large structures than has been realized in the past.

Pulser techniques involve even newer technologies which are, even now, continuing to be developed at a rapid pace. Even so, there has been recent experience to show that the method is well adapted to the assessment of earthquake motions. Basic research is being conducted for the National Science Foundation by Agbabian Associates, which will clarify a broader class of applications of the pulser methods. Subsequently, these findings can be extrapolated to include applications to nuclear reactor structures and equipments. This information will be available in late 1979 and will continue to be forthcoming over the next several years.

4.1 HIGH-EXPLOSIVE TESTS

The use of high explosives to produce a ground-shaking environment provides, in principle, all of the necessary energy to simulate an earthquake. Aside from the obvious risk of causing damage to the reactor because of this motion, the possibility of causing collateral damage to nearby structures must also be considered. The principal advantage of these high-level tests is that the verification can be accomplished at high-confidence levels because the test approaches actual earthquake intensities. However, because of the high-energy levels possible with this technique, limitations on the magnitude of motions must be imposed to reduce the probability of potential damage to facilities. The decision to specify the actual level to conduct the test rests with the plant manager.

A typical high-explosive test configuration for reactor verification is shown in Figure 4-1. The test includes a number of explosive charges buried in the vicinity of the structure. The variables that affect the composition of the shaking motion include the number of charges, their energy density, their spatial arrangement, their ignition timing, and the depth of burial. The function of the test is to provide an earthquake-like motion of the structure foundation. This earthquake-like motion (which has the composition of a typical earthquake except that it occurs at a reduced amplitude) has variables of amplitude, duration, frequency content, and directional characteristics.

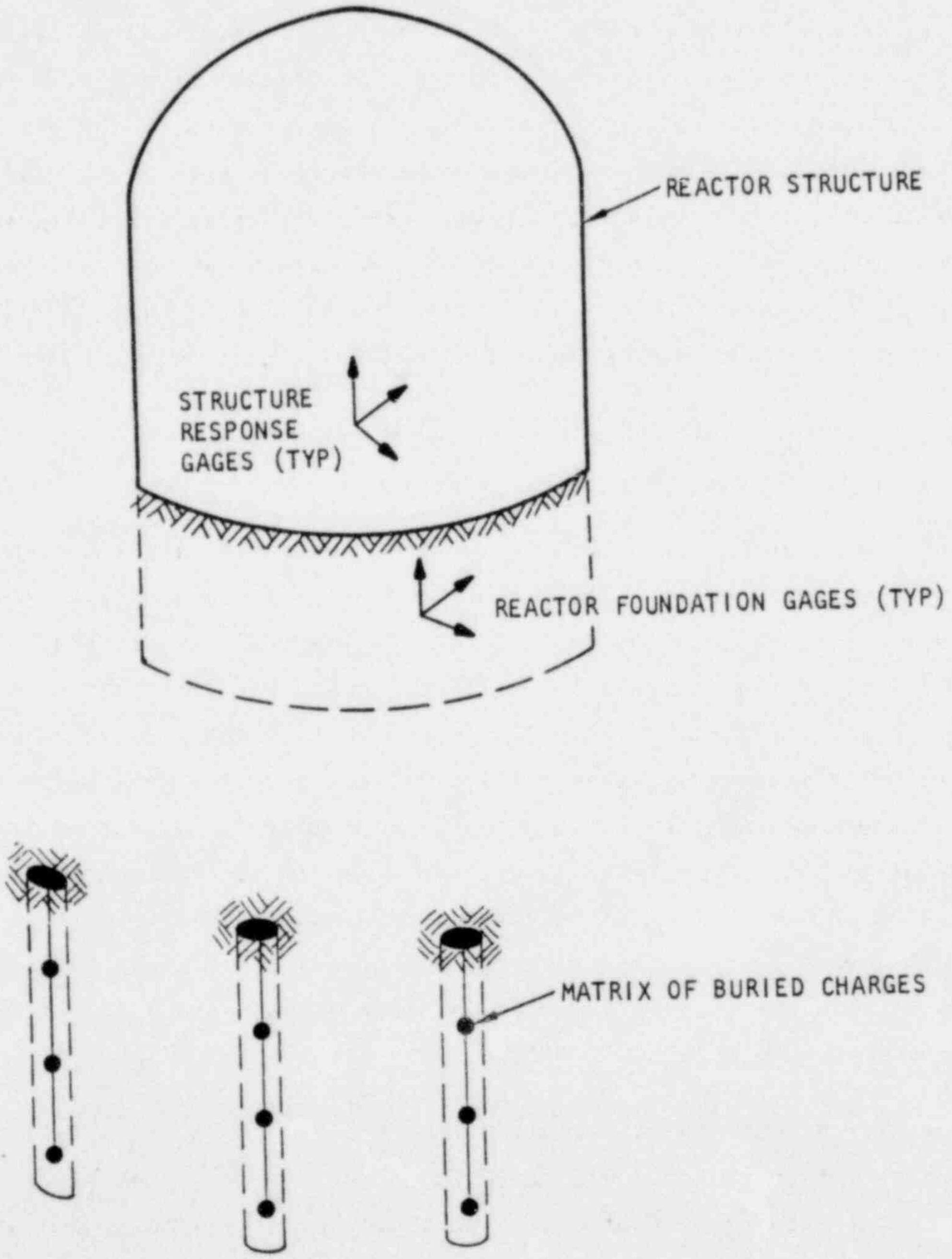


FIGURE 4-1. LAYOUT OF GROUND EXPLOSION TESTS

By controlling the variables of the charge array, it is the purpose of the test to control the variables of the resultant motion. In designing the test, the additional variables that relate the placement of explosives and the resultant motion are medium type, density, stiffness, strength, moisture content, stratigraphy, anisotropy, and other factors. Clearly these variables are site dependent and largely nonlinear. Furthermore, each plant will be subject to unique facilities earthquake susceptibilities and different earthquake threats. As a consequence, each high-explosive test will be tailored to the requirements of a particular plant, and although generalized test procedures can be prepared, each test plan will be unique to each plant.

4.1.2 FACTORS AFFECTING CHARGE ARRAY SELECTION

Buried charge arrays have been used in both military and nonmilitary applications to generate controlled ground motions. For a number of years, the U.S. Air Force has experimented with the Cylindrical In-Situ Test (CIST) (Davis, 1974) to provide a basis for selecting nonlinear soil parameters for the use in computer programs to predict ground motions and for the calculation of site/medium interaction. Essentially, the test provides data which is compared to predicted motions by varying the parameters. The parameters of a mathematical soil model are iterated in order to achieve acceptable correlation to the test results. A typical CIST configuration is shown in Figure 4-2. The CIST charge is designed to excite the medium so that material models can be optimized. No great care is taken to generate a specific time history and in this sense it differs from the present plan.

A more direct military application of buried high explosives to produce ground motion has been developed by the Air Force in the DIHEST program. DIHEST (Direct Induced High Explosive Simulation Technique) has been used to simulate the ground motion caused by the crater formation from surface-detonated nuclear weapons. This motion often has been combined with HEST (High Explosive Simulation Tests) tests that simulate the airblast also caused by nuclear weapons. The configuration of HEST and DIHEST is shown in Figure 4-3.

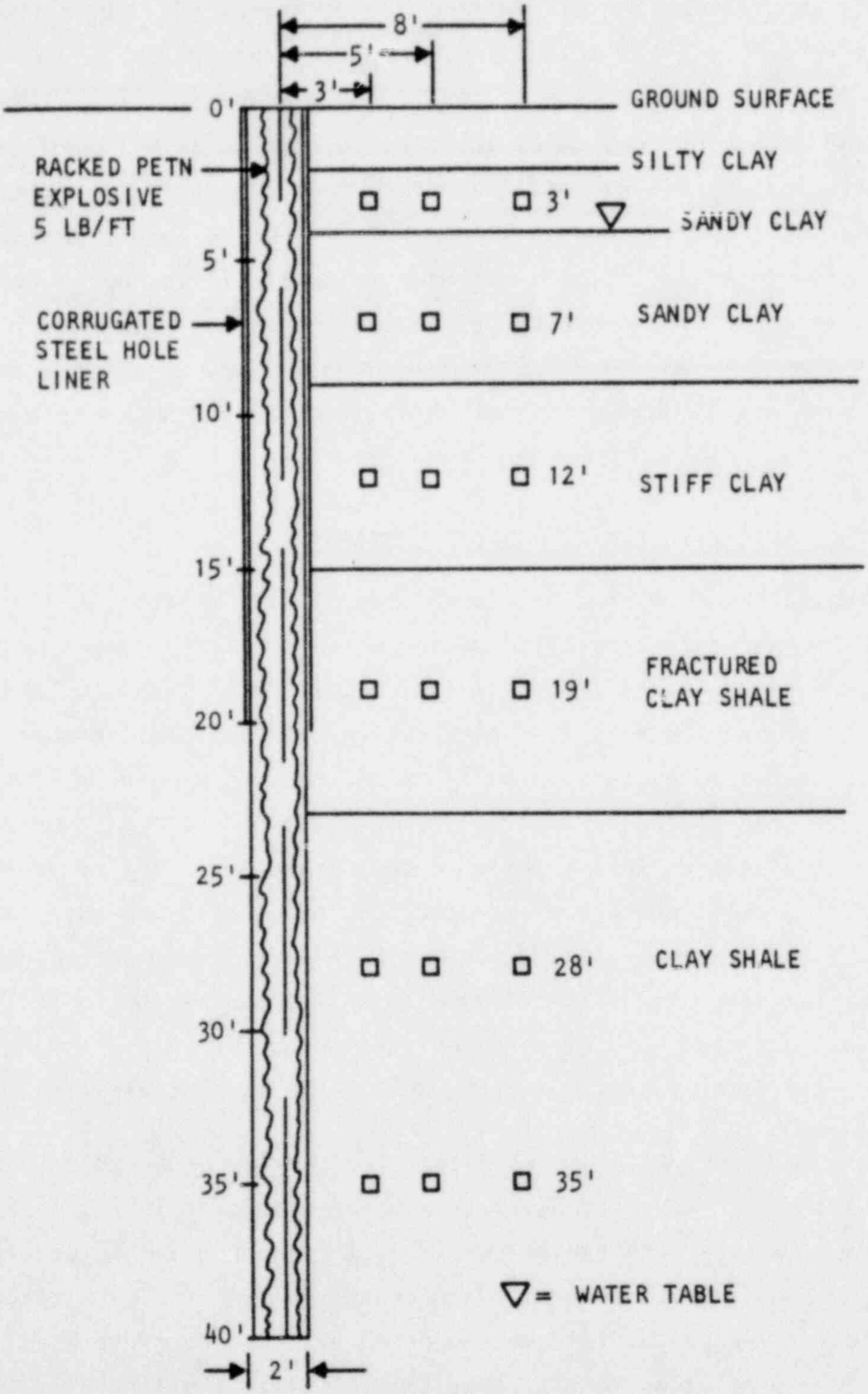


FIGURE 4-2. TYPICAL CIST EXPLOSIVE HOLE AND GAGE CONFIGURATION (Davis, 1974)

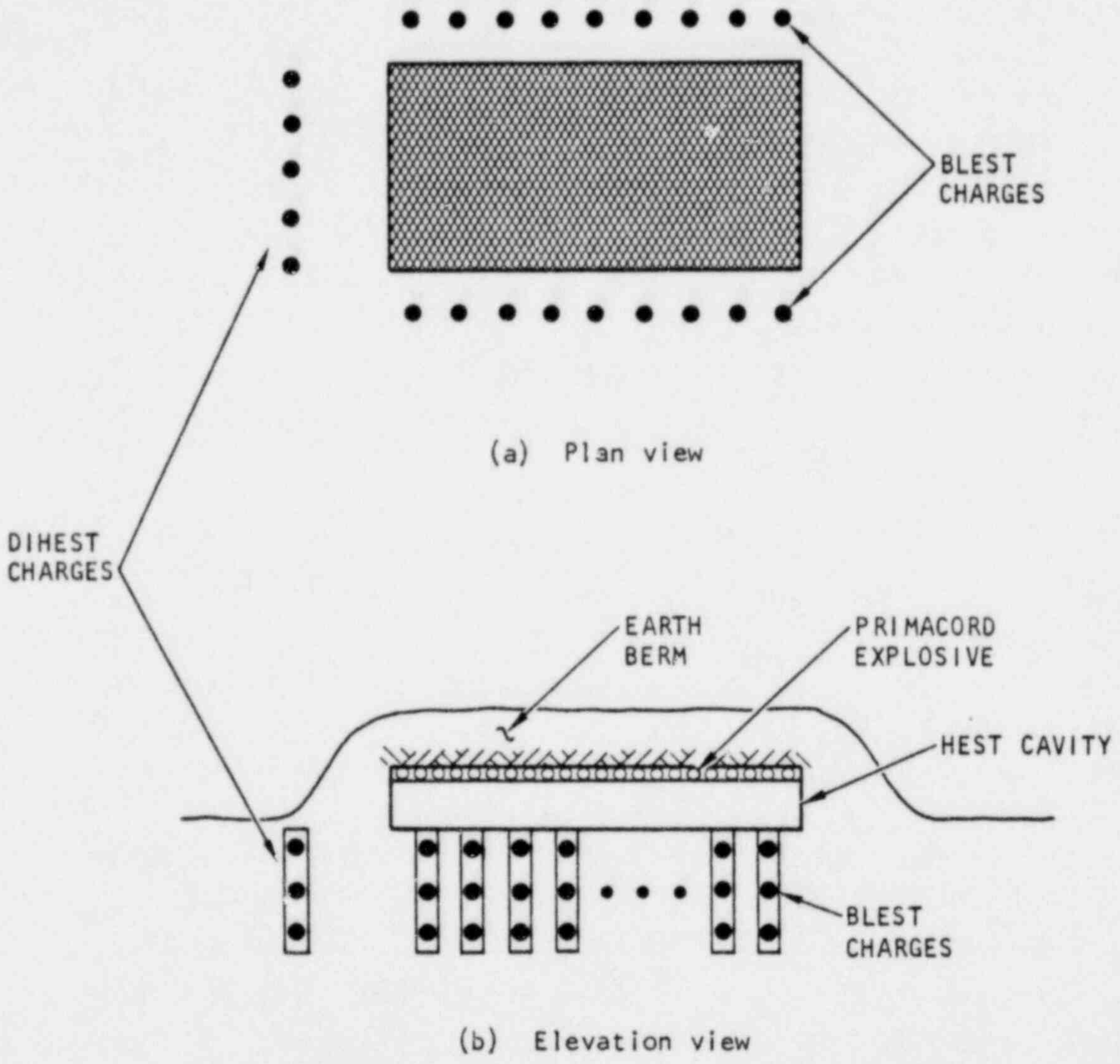


FIGURE 4-3. SKETCH SHOWING HEST CAVITY AND DIHEST AND BLEST BURIED CHARGES

HEST also has been combined with BLEST (Berm Loaded Simulation Technique), which is designed to prolong the duration of the HEST airblast environment. The idea of these tests is to subject buried silo housed missiles to very severe nuclear type environments.

The work performed by the military for testing the survivability of missile systems has been extended to nuclear reactor facilities (Higgins et al., 1977). It has been shown that reasonable earthquake motions could be achieved if: (1) multiple charges are used, (2) longer burn times are allowed, (3) the explosive is decoupled from the ground by placing the explosives in cavities, (4) the explosive array is designed to focus the energy onto the facility, (5) sequential firing is provided, (6) barriers or trenches are used to enhance the motions, and (7) the charges are placed far enough away from the facility to attenuate high frequency.

Earlier, Chrostowski et al. (1972) had investigated a variety of responses of the EGCR (Experimental Gas Cooled Reactor facility at Oak Ridge) plant to buried high-explosive charges. They too have demonstrated that excitation by buried explosive charges is feasible, and they recommended this technique as a viable approach to conducting verification studies of reactor facilities.

In order to design a charge array (in terms of spatial arrangement and time sequencing) that will simulate an earthquake, it is assumed that multiple charges will be required. Chrostowski notes that their studies have indicated that the precise explosive, i.e., its detonation rate (and presumably its composition), will not markedly affect the ground motion produced; that the response appears to be essentially a function of energy available in the explosive. Further, he notes that an increase in the magnitude of the charge has the tendency to increase the amplitude response and to shift it into lower frequency domains. The amplitude dependence appears to adhere to the cube root scaling law of the charge weight. By controlling the time delays between explosions, the duration of ground response can be manipulated. The character of the motion (signature) can be controlled by the distance of the charge from the facility and the depth of charge burial.

A consequence of the use of multiple charges is that irrespective of the spectral content of motions caused by individual explosions, proper sequencing of the explosions can concentrate the energy into the frequency bands of special interest to earthquakes. This has been demonstrated by designing pulse trains for mechanical pulsers (Masri, 1976), and it is clearly evident by examining the spectral content of a sine train composed of n repeated pulses. The pulse is defined as

$$f(t) = \begin{cases} \cos \omega_0 t, & -n < t < n \text{ cycles} \\ 0 & \text{, otherwise} \end{cases} \qquad (4\text{-}1)$$

In Figure 4-4, it can be seen from the Fourier transform of $f(t)$ that frequencies near the period of the train can be intensified without markedly affecting surrounding frequencies. Thus, by the proper design of the charge array, the frequency domain of the resultant motion can be populated in such a way as to reproduce a realistic, scaled earthquake. The capability to construct a signature in this way is important, since it allows the test designer to avoid excessive high frequency and tends to preclude testing equipments and structures in frequency domains outside of the criterion spectrum.

4.1.3 TEST DESIGN CONSIDERATIONS

This study cannot specifically delineate high-explosive test design because of the many important factors governing the selection and planning of the charge array. The most important of these is the site specific considerations. Each site will have a unique geology and physical arrangement of reactor facilities. Some of the factors to be considered in designing the array are discussed in Section 5; these include an iterative procedure in charge selection and placement.

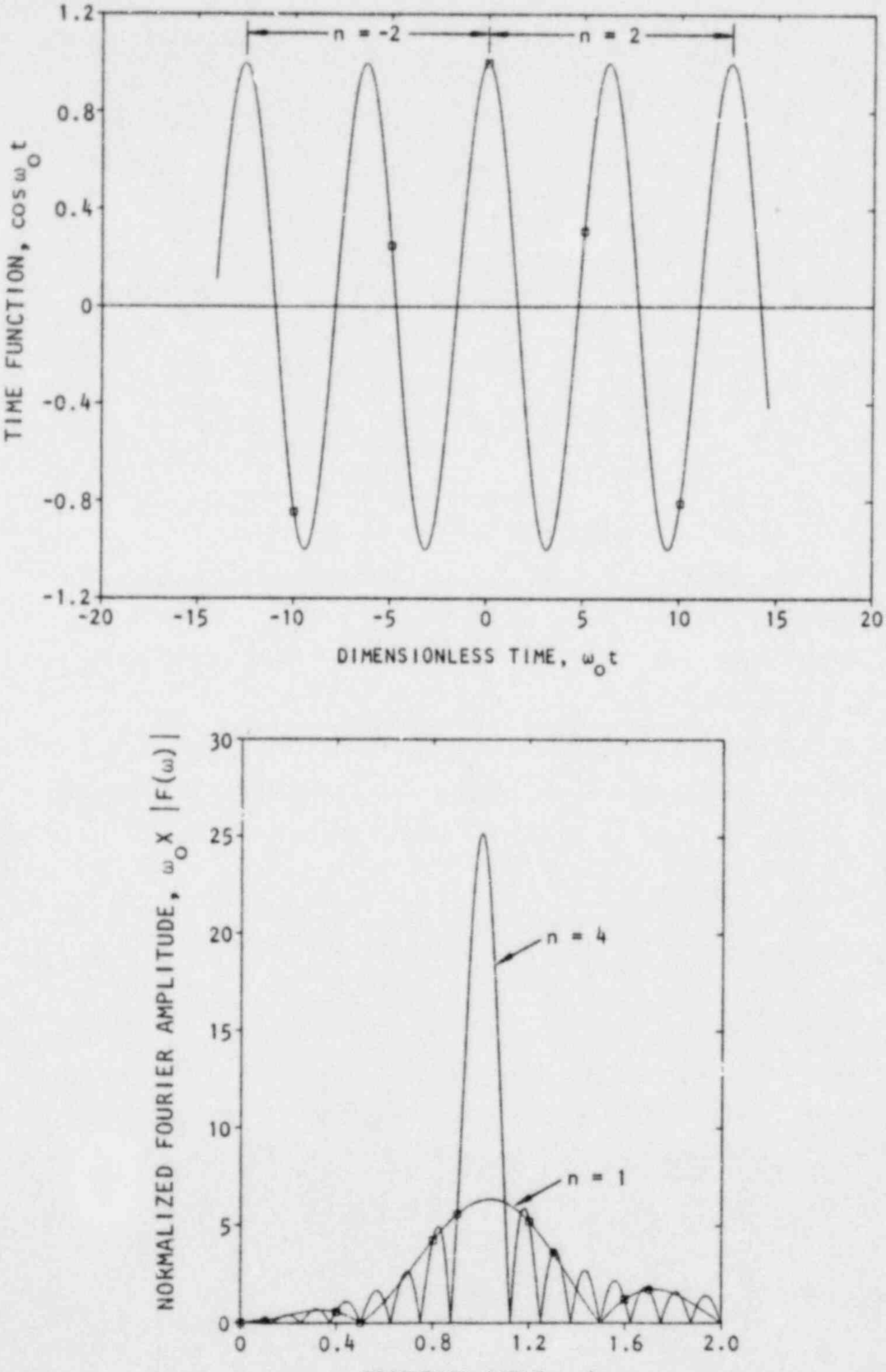


FIGURE 4-4. COSINE TRAIN SPECTRAL CONTENT

As noted earlier, it is necessary that the frequency spectrum be controlled to concentrate energy in the earthquake frequency band and to preclude excessive high frequency disturbance of the facility. Such frequencies, if allowed to reach the facility, could cause malfunctions of sensitive equipment, especially electronic gear. Such a malfunction would have no meaning to the verification assessment since it is caused by an environment unrelated to earthquakes. Abrahamson (1979) has devised a means for placing charges in such a way as to limit the high-frequency content. This would be especially important where the charges must be placed in or very near to bedrock. In soil sites the problem is largely alleviated because of the natural high-frequency filtering afforded by the medium.

On the other hand, it is also necessary to ensure that the surrounding community is protected from ground motions induced by the explosive charges. Again, the magnitude of this problem will depend on the condition at the specific site. Where such protection is required, it may be possible to mitigate the ground shock radiating outward from the site by trenching or otherwise providng a barrier between the charges and other nearby structures.

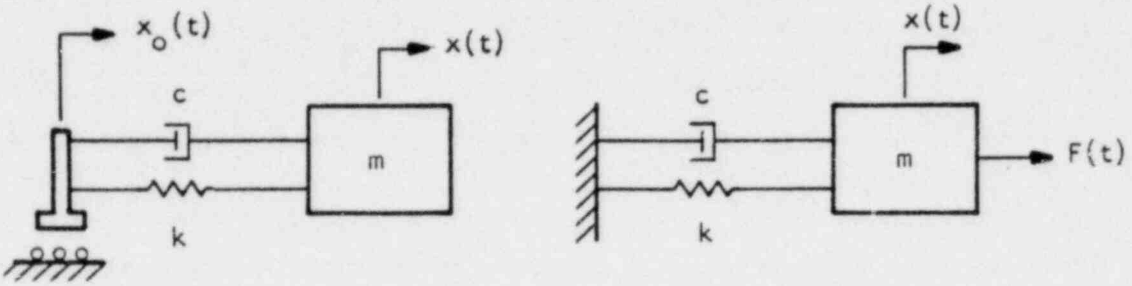
A very important part of high-explosive testing will involve the preparation of a test planning document in which site specific problems are addressed in addition to the means for planning the charge array configuration. The plant manager will require specialized assistance in developing the test plan.

4.2 PULSER TESTS

Traditional earthquake simulation testing applies excitation at the mounting points of equipments or subsystems or at the base of structures. Thus, the input motions are introduced in the same way that they occur in natural seismic events. The high explosive test technique of Section 4.1 is in accordance with this tradition.

By contrast, pulser tests applied to in-place equipments, subsystems, or structures are accomplished by locating the pulsers in such a way as to cause the equipment or structure to respond as it would in an earthquake. Dynamically, the equivalence between the traditional approach and the pulser approach is illustrated in the simple schematic of Figure 4-5 (Crandall, 1958). The equation in Figure 4-5 incorporates, for an earthquake base motion excitation, a continuous force excitation function to produce an equivalent response. Continuous force excitation at SSE levels or fractions thereof for major structures or massive equipments is impractical due to (1) energy requirements, (2) safety considerations, (3) waveform control and energy management, and (4) portability of excitation test systems.

Individual pulsers do not produce the continuous functions required for earthquake simulation. Since each pulser superficially provides a response whose appearance is quite different from a continuous excitation signal, it becomes necessary to select a pulser array which produces a motion of the system that matches the response produced by a continuous earthquake. The fidelity of this response is determined by an appropriate error criterion (Masri et al., 1975). The use of error criteria require that the continuous earthquake response motion of the structure or equipment be known. To accomplish this, a computer model of the structure under study is used to predict the response of the system to an earthquake, usually at sub-SSE levels. To accomplish the test, pulsers must (1) produce large energy outputs; (2) provide controllable amplitudes, pulse durations, and pulse onset times; and (3) be portable (Safford et al., 1974b). Under these conditions, the "criterion response" can be calculated and used to obtain the pulse trains for each of the pulsers. Thereafter, the structure, equipment, or subsystems responses are extrapolated to full SSE levels by procedures delineated in Section 5.



(a) Base motion excitation

(b) Pulser excitation

$$\ddot{X} + 2\delta\omega_n\dot{X} + \omega_n^2 X = \omega_n^2 f(t)$$

where

δ = Damping ratio

ω_n = Natural frequency (undamped)

$$f(t) \begin{cases} F/K & \text{force excitation} \\ \frac{X_o}{\omega_n^2} & \text{base motion excitation} \end{cases}$$

FIGURE 4-5. SCHEMATIC OF DYNAMIC EQUIVALENCE FOR BASE MOTION EXCITATION AND FORCE EXCITATION

4.2.1 PULSER DEVELOPMENT

A hybrid mechanical/hydraulic pulser was developed in 1973 to induce transient time histories on massive equipments (Safford et al., 1974a). A typical application is shown in Figure 4-6, in which a shock-isolated control room weighing 200,000 lbs was driven to duplicate predicted motions of the equipment in-place, as installed, and functionally operating. These tests were performed at 100% of the expected environment. The data from these tests are shown in the shock spectra of Figure 4-7 (Safford et al., 1977). The predicted response in the figure was obtained from a mathematical model and this response was used as the criterion function. The design of the pulser system was projected to produce a simulated response of the equipment as shown on the figure. The actual test response is also shown. In general, this early test showed a tendency to overstimulate the equipment, which was traced to an inadequacy of the techniques used to design the pulser system. Later improvements in the computer optimization schemes for pulser design have improved the performance of pulser systems.

A mechanical pulser or the mechanical part of a hybrid pulser is a metal-cutting device in which a multiple blade cutter is driven with great force to cut through a series of metal projections called nubbins. Judicious design of the cutter, projection shapes, cutting velocity, and energy source produces various pulse amplitudes, shapes, and durations. The high force output mobilizes the important modal responses of the equipment. For large structures, unidirectional pulsers generate force signals with a large static component and they can be programmed to populate the ultra-low-frequency spectrum. A schematic of a hybrid pulser is shown in Figure 4-8. By controlling the fluid flow in the cylinder and the pressure in the hydraulic or pneumatic source, the force-time history acting on a test article is controlled to produce the pulse train.

Subsequent to the early development of pulsers as shown in Figure 4-8, four improved versions have been designed and used for tests. These units produce outputs ranging from 125 lbf-sec to 4,700 lbf-sec (AA, 1979a).

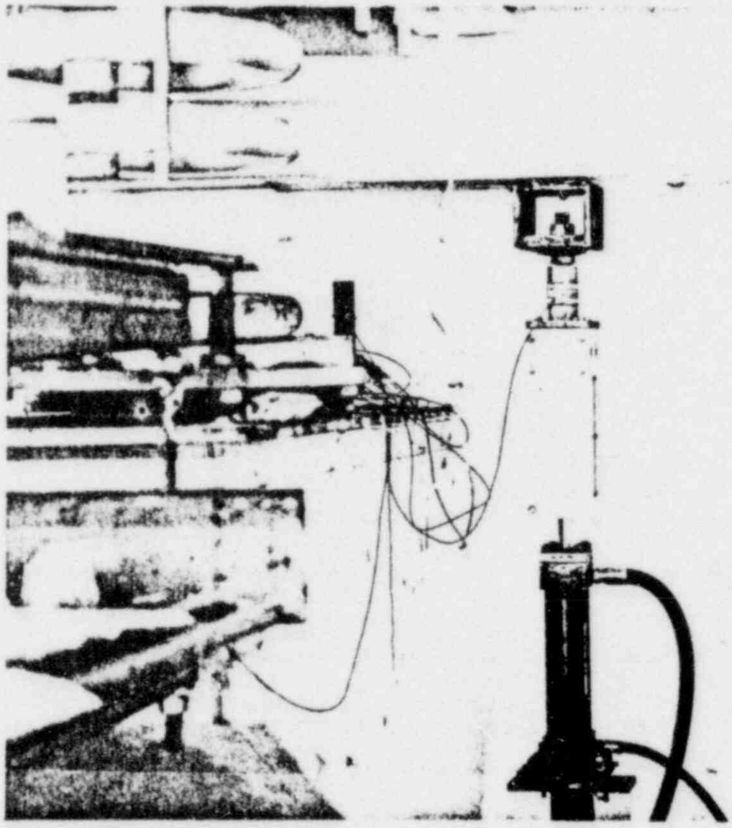


FIGURE 4-6. PULSE TEST CONFIGURATION FOR CONTROL ROOM PLATFORM SHOWING ONE OF FOUR UNITS REQUIRED

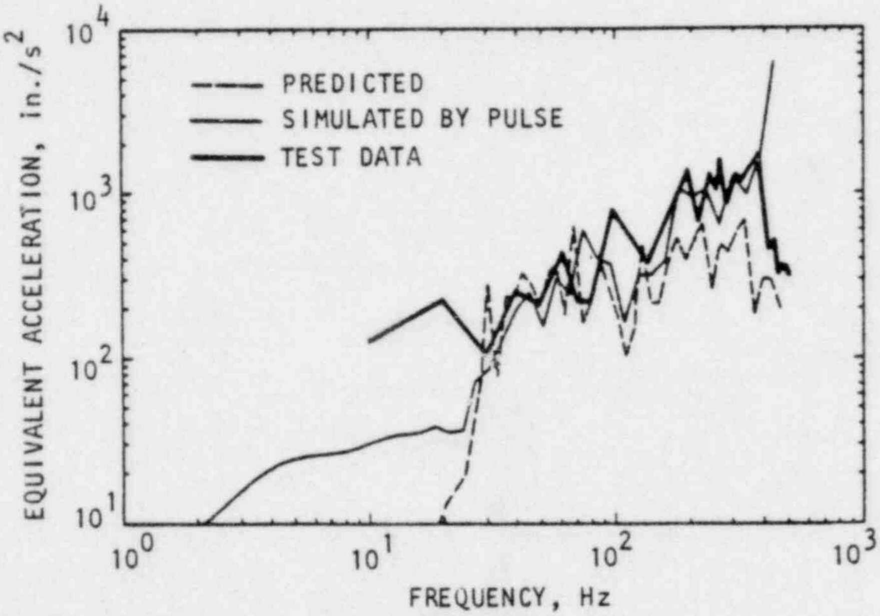


FIGURE 4-7. SHOCK-SPECTRA COMPARISON OF PREDICTED, PULSE-SIMULATED, AND PULSE-TESTED RESPONSES OF EQUIPMENT

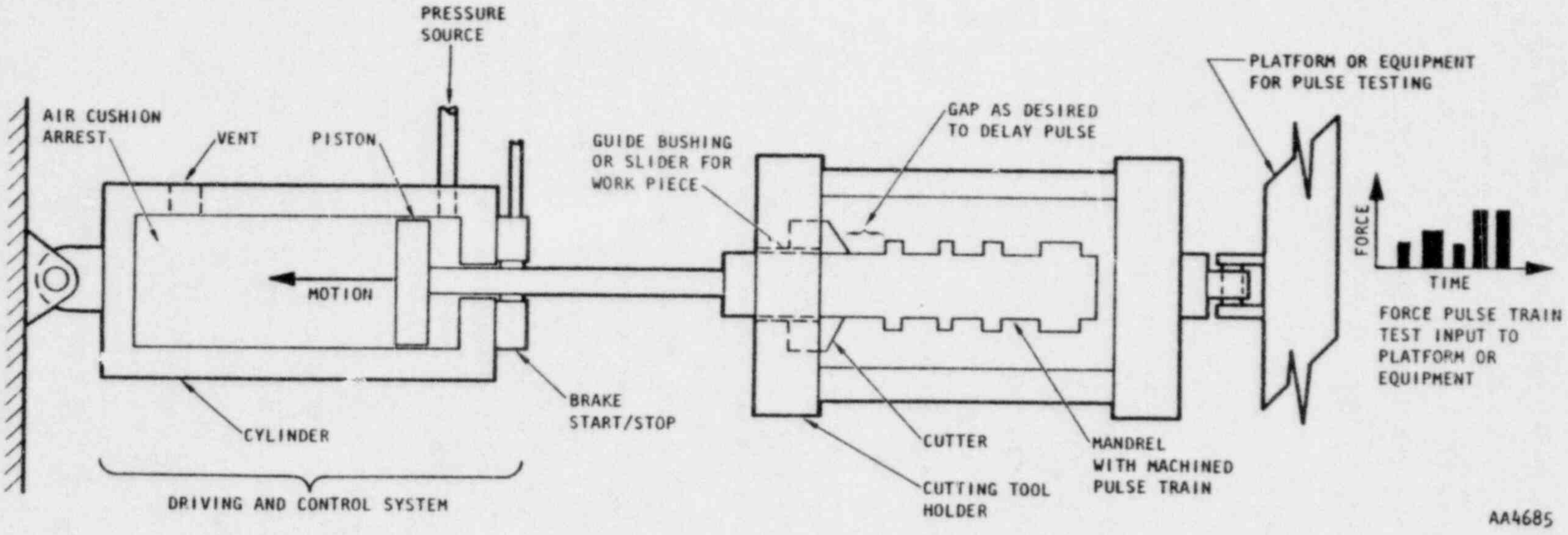


FIGURE 4-8. PULSE-FORMING DEVICE WITH DRIVING AND CONTROL SYSTEM

Preliminary designs have been prepared for a 300,000 lbf-sec machine and, for a foreign client, a 3,000,000 lbf-sec machine. A current project employs relatively small units in two independent orthogonal axes to simulate transient motion in electronic equipment to acceleration levels up to 1000 g in a frequency bandwidth ranging between 20 Hz to 4 KHz (Schuman et al., 1979).

4.2.2 REACTOR FACILITY APPLICATION

The test program presented in this report foresees the use of mechanical pulsers to test Class 1 equipment and subsystems to simulate earthquake environments. Test levels up to an SSE in all axes of motion may be simulated. The actual levels are governed primarily by safety considerations. In earthquake simulation, one end of the pulser is attached to the equipment and the other is attached to the primary structure. This arrangement is possible because the motion feedback by the primary structure from load reactions by the pulser have in past tests proved to be minimal due to the gross impedance mismatch between primary structure and equipment. However, where feedback is significant, prior compensation may be made in programming the force pulse train to account for the effect.

Another type of pulser suited to large structures such as containment buildings are fluid reaction rocket motors. Such units are attached directly to a structure. The output force results from the supersonic expulsion of gases at the nozzle. Several types of rocket motors, as listed below in general order of increasing thrust, are available for application depending upon impulse requirements:

- Cold gas (metered and blowdown)
- Gas/hydraulic (metered and blowdown)
- Steam (metered and blowdown)
- Monopropellant (metered)
- Solid fuel rockets (blowdown)

These rocket systems are currently under application development to simulate earthquake motions in large civil structures. This validation demonstation is being conducted by a grant from the National Science Foundation (Safford, 1977). The first demonstation will be conducted in the fall of 1979 by pulse simulation of large structures to earthquake hazards on a 4/9 scale, three-story moment-resistant, steel-frame structure at the Earthquake Engineering Research Center, University of California, Berkeley. The results of the pulse simulation tests will be compared to response measurements previously made on this same structure when it was tested (base motion input) on the Berkeley two-axes vibration machine for an El Centro earthquake motion (Clough, 1975).

Fluid reaction devices to be used, as illustrated in Figure 4-9, will be configured as cold gas or steam rockets. These devices, having programmable thrust metering, are currently in design and development. Full-scale, multiaxis earthquake tests on an existing large structure will be performed in the spring of 1980 at levels ranging from linear response up to and including the yielding and post-yielding regimes. For these tests, monopropellant and solid fuel rockets will be used in addition to lower level tests by the cold gas and steam rockets.

The cold gas, steam, and monopropellant motors will provide thrusts up to 15,000 or 20,000 lbf. Metering provides, in addition to on-off control, orifice area control to generate preprogrammed thrust levels. The so-called blowdown configurations are used to generate one-shot high thrusts. These devices are initiated by disc rupture for a fixed nozzle size (thrust) and with a time duration dependent upon the reservoir size of the rocket chamber. The extensive developments in rocket technology provide a large class of solid fuel chemical rockets that may be adapted and installed for testing of large civil structures up to major earthquake levels. The class of rockets available to meet these applications range in diameter from 3 in. to 30 in. and have thrust durations from 0.125 sec to 5 sec. Thrusts range from 5000 lb to 130,000 lb. Modifications of combustion chambers will be required for load transmissions to building hard points and in chamber length to achieve

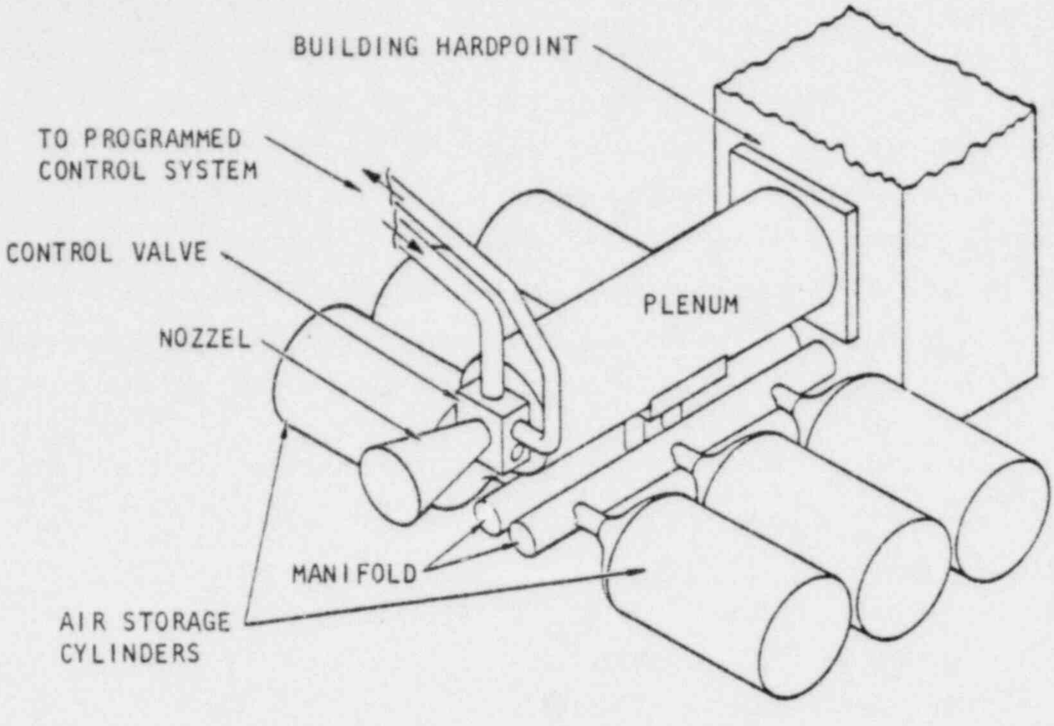


FIGURE 4-9. SKETCH OF COLD GAS THRUSTER BLOWDOWN SYSTEM

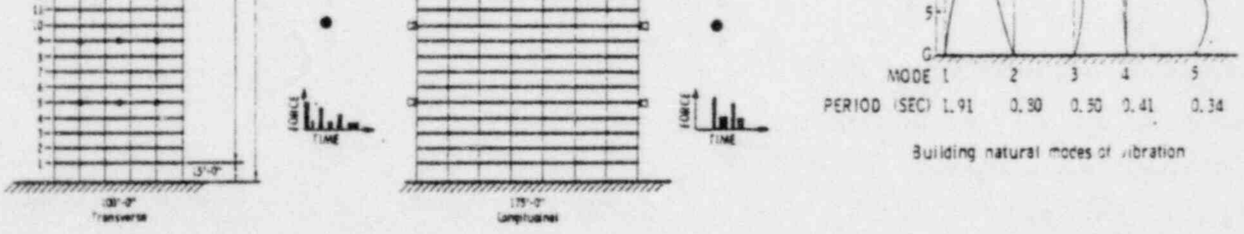


FIGURE 4-10. GAS PULSERS ARRAYED FOR EARTHQUAKE SIMULATION TEST OF A MULTISTORY BUILDING

desired thrust durations. Rise time and tailoff of thrusts, empirically determined, are included as pulse profile modifications in the optimization algorithm (Masri et al., 1976) for programming the pulses.

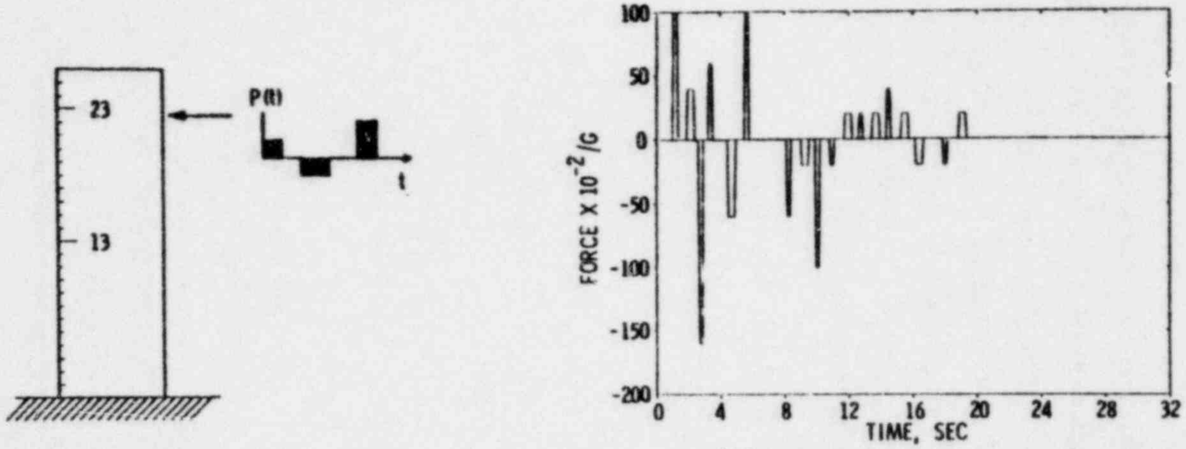
An example of the application of fluid reactor devices to a 25-story reinforced concrete structure is shown in Figure 4-10. For the simple case of pulse excitation only on the 23rd floor as shown in Figure 4-11, 10 pulses on one side and 8 pulses on the other side of the building will be required to match the El Centro earthquake-induced building motion (Masri et al., 1976). Pulse trains are varied in amplitude, duration, and initiation time as may be observed in the figure by the optimization algorithm.

4.3 SYSTEM FUNCTION AND DIAGNOSTIC TESTS

Methods of excitation to measure system function characteristics (see the appendix for discussion) include:

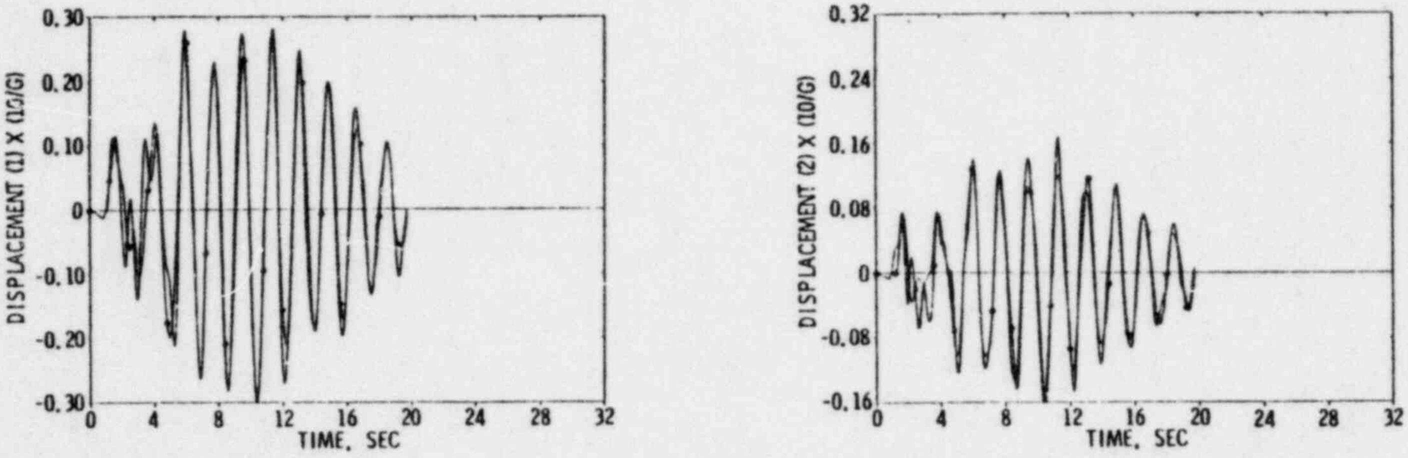
- Slow sine sweep and dwell
- Random
- Rapid sine sweep (chirp)
- Impulse
- Pulse train

The selection of physical hardware depends on the force levels, shaping characteristics, and bandwidths required. The most commonly used force-function generators are electrodynamic and electrohydraulic shakers that produce continuous periodic (usually sinusoidal) functions that are controllable in amplitude, time duration, and frequency. With sophisticated control systems, these devices are also capable of generating random and complex force functions (chirp) as well as simple pulses. Higher capacity electrohydraulic shakers have capacities of up to 50,000 lbf.



(a) Pulse train location

(b) Optimum pulse train



(c) Displacement of floor 23

(d) Displacement of floor 13

FIGURE 4-11. COMPARISON OF EXACT —— AND SIMULATED -o-o- MOTION OF 25-DOF BUILDING. CRITERIA INPUT IS EL CENTRO GROUND MOTION. PULSE TRAIN APPLIED TO 23RD FLOOR.

Rotating eccentric mass shakers for slow sine wave and resonance dwell exist in several universities, government laboratories, and private corporations. Capacity of output forces vary up to 100,000 lbf.

Shock machines, impact hammers, pulse train generators, and explosives produce a second family of impulsive or transient driving functions. These types of functions may include many pulses of varying forms (e.g., half-sine, triangle, square), depending on the required input. Important considerations with these devices are the generation of continuous input amplitude functions in the frequency bandwidth of interest and adequate output motion generation in the structure for favorable signal-to-noise ratios.

A mechanical force pulse train generator of the type described in Section 4.2 is in general use for the measurement of inertance and transfer functions of structures comparable to nuclear power plants (Yates, 1980). This pulser is illustrated in Figure 4-12 where a 5000 lb carriage fitted with a steel metal-cutter in the anterior face slides down a rail system to engage a mandrel stacked with alternating aluminum cylinders (or nubbins) and spacers. As the cutter cuts sequentially through the nubbins, forces are induced in the structure so that the load is applied to a building in a series of pulses called a "pulse train." The nubbin system is designed so that the energy transmitted to a structure is constrained to have the desired spectral content. In one particular case, the test data are currently being used to determine the resistance of a structure to earthquakes. Accordingly, the pulser parameters were designed to concentrate the energy applied to the building within the frequency range below about 35 Hz. This particular pulser has the ability to produce up to 10 individual pulses and force output for each pulse up to 100,000 lbf.

An example of test data for the pulser illustrated in Figure 4-12 is shown in Figure 4-13 (AA, 1979a). The tested facility is a two-story reinforced concrete structure 460 ft x 300 ft, specifically designed to resist strong earthquake motions. The pulser parameters were designed to produce

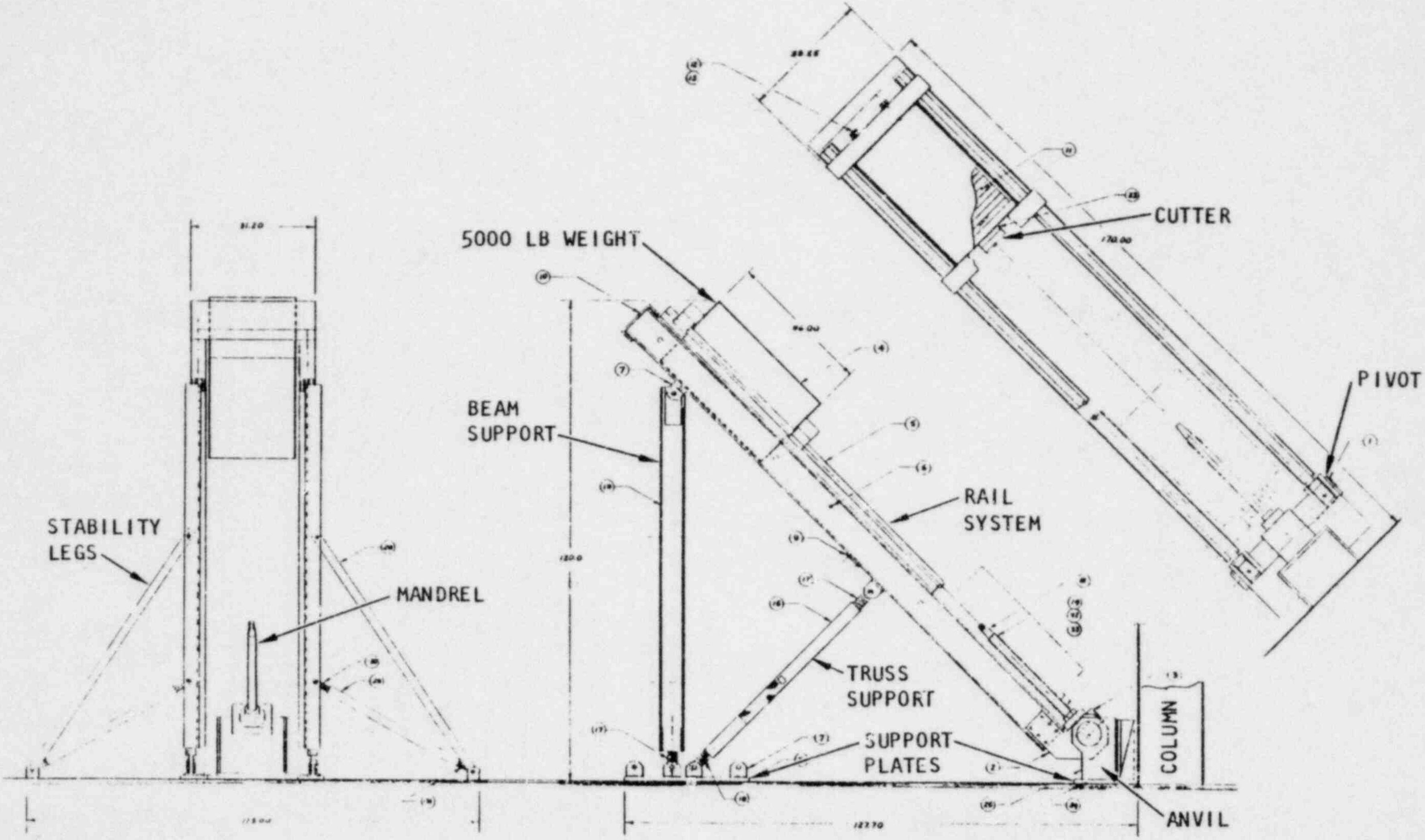
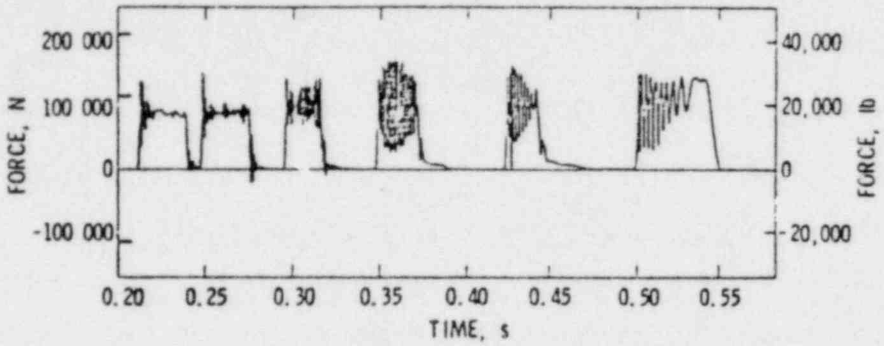
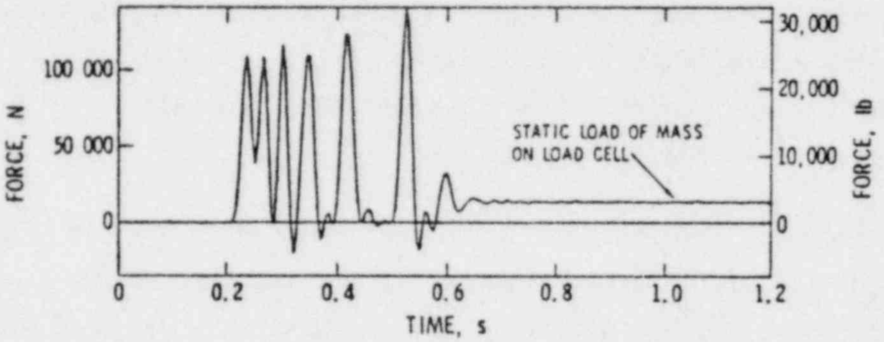


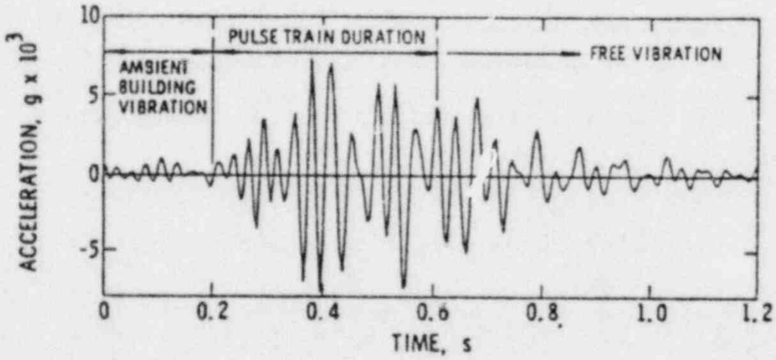
FIGURE 4-12. ASSEMBLY — PULSE TRAIN GENERATOR



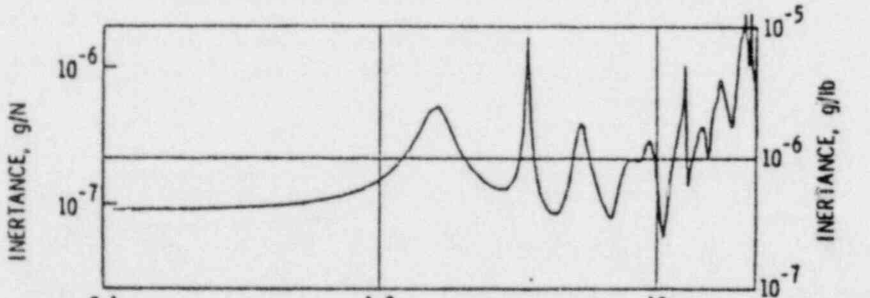
(a) Raw input force-time history



(b) Filtered input force-time history (0 to 20 Hz)



(c) Acceleration-time history (0 to 20 Hz)



(d) Transfer function (acceleration divided by force)

FIGURE 4-13. TYPICAL DATA RECORDS FROM PULSE TRAIN TESTS AND RESULTING TRANSFER (INERTANCE) FUNCTIONS COMPUTED FROM DATA six pulses of approximately 27,000 lbf of force each for a total pulse train duration of about 1/3 sec.

A typical raw input force into the building is shown in Figure 4-13a. When filtered to 40 Hz to conform to the earthquake frequency domain, the pulse takes the form shown in Figure 4-13b. A typical acceleration response of the structure is shown in Figure 4-13c. The averaged transfer function magnitude between several force inputs and several acceleration outputs obtained from repeated pulse train tests is illustrated in Figure 4-13d. This averaging is an essential requirement for all systems functions to minimize errors due to noise (see the appendix).

When modal surveys are to be performed, data such as illustrated in Figure 4-13 must be obtained from sufficiently enough locations in the building to generate a map of the mode shapes (Richardson, 1976; Klosterman, 1975). Inverse Fourier transformation of functions similar to Figure 4-13d are also made to obtain time domain inpulse functions. These impulse functions are convolved with pulse time histories to generate motions in a structure or equipment to match predicted earthquake motions. This procedure is discussed in the appendix.

Random excitation, chirp (rapid sine sweep), specially configured pulse trains, and ground explosion tests are used to quantitatively define system nonlinearities. The procedures used to identify these functionals are provided in the appendix. Once these nonlinear functionals have been established, they are used similar to transfer functions in the prediction of response motions and for the development of pulse trains for environmental simulation tests.

The question of damage and failures in a large complex structure or the residual integrity of a structure following an earthquake can be quantitatively accessed by comparison of structural system functions. The quality of measured system functions has reached a state where slight structural changes may be detected (Fowler, 1978; AA, 1978). For example, damage may occur in a redundant structure at a weld or a major concrete failure in a reinforced column. A comparison of transfer functions measured before and after an earthquake can disclose damage and provide guidance for subsequent evaluation and assessments. While the damage to the structure may have been caused by the low frequencies of an earthquake, its detection must include the frequency specturm to about 5 KHz.

Material damping of the primary structure at higher stress levels (as in an earthquake) generally follows the relationship given below (Lazan, 1958):

$$D = J\sigma^n \tag{4-2}$$

where

D = Specific damping (in.-lb/in.^{3} cycle)
J = Constant for material (damping constant)
n = Constant for material (damping exponent)
σ = Stress

Measurements for high stress damping may be taken on a structure at areas considered critical from dynamic analysis. The stress damping information obtained may be subsequently used in response prediction for earthquakes.

Dynamic exciters (vibrators or pulse generators) are used to locally load an area to progressively higher stress levels as shown in Figure 4-14. Vibrators are useful only below the tensile strength level of the concrete. Unidirectional pulse generators may be used to higher levels due to compressive loading of the concrete. From the resulting drive point and transfer functions obtained for each load level, the dynamic damping and resulting stresses are obtained. Stresses generated have an elliptical integral relationship with the locally applied dynamic load. This data permits the establishment, in the as-built condition, of the effective stress-damping relationship for each location in the structure surveyed (Safford, 1971).

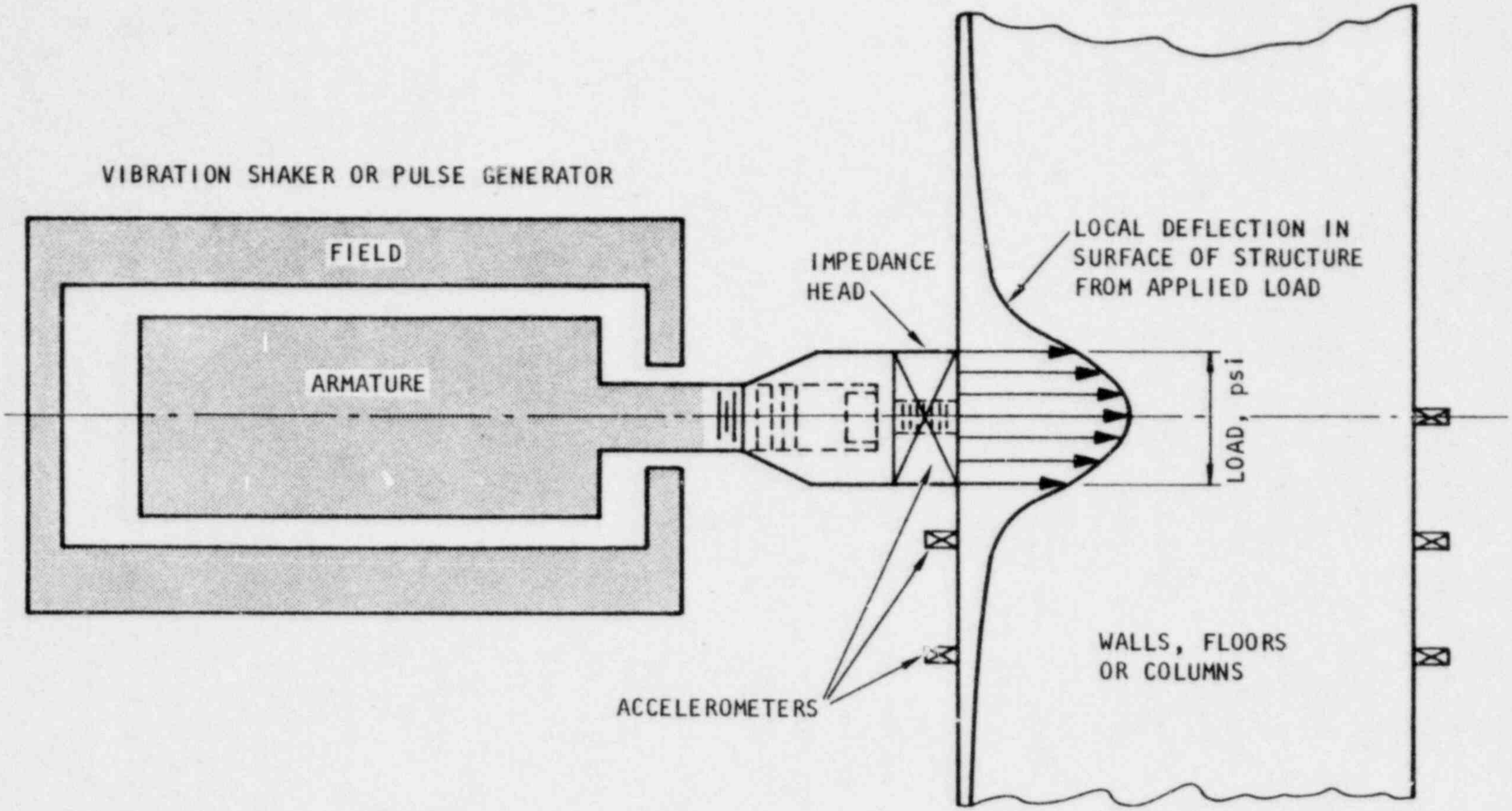


FIGURE 4-14. MEASUREMENT METHOD TO DETERMINE MATERIAL DAMPING IN A STRUCTURE AS A FUNCTION OF EFFECTIVE LOCAL STRESS

SECTION 5

PROCEDURES FOR PERFORMING VERIFICATION TESTS

This section presents technical descriptions of the procedures necessary to perform verification tests of nuclear reactor plants. These descriptions provide a basis for the development of test plans and related information covered in subsequent sections.

The verification tests discussed in this document are all of the impulsive load type. Accordingly, they share common characteristics that translate into certain redundancies in methodologies, irrespective of the method by which the impulsive load is applied. In the most comprehensive test, the reactor structure and all of its internal equipments would be subjected to an earthquake-like motion; in effect, an earthquake environment would be created by the use of high explosives in the soil or rock. In an alternate approach, loads would be applied directly to structures via non-explosive devices to make them, or portions of them, respond in an earthquake-like manner. Internal equipments would also be excited, but any motion of the surrounding medium would be incidental. In a final approach, internal equipments or subsystems would be subjected directly to an earthquake-like environment. Any motion of the building as a whole or of the surrounding medium would be incidental to the test.

This section is organized to discuss these three tests individually. Because the high explosive technique is most comprehensive, it is discussed first. Subjects pertinent to all tests will be discussed in the context of the high-explosive test approach and referenced in subsequent test descriptions.

5.1 SIMULATION OF EARTHQUAKE-LIKE MOTION USING HIGH-EXPLOSIVE TECHNIQUES

The overall approach for conducting high-explosive field tests on nuclear reactors and associated equipments is depicted in the event chart shown in Figure 5-1. Basically, the intent of this test is to create

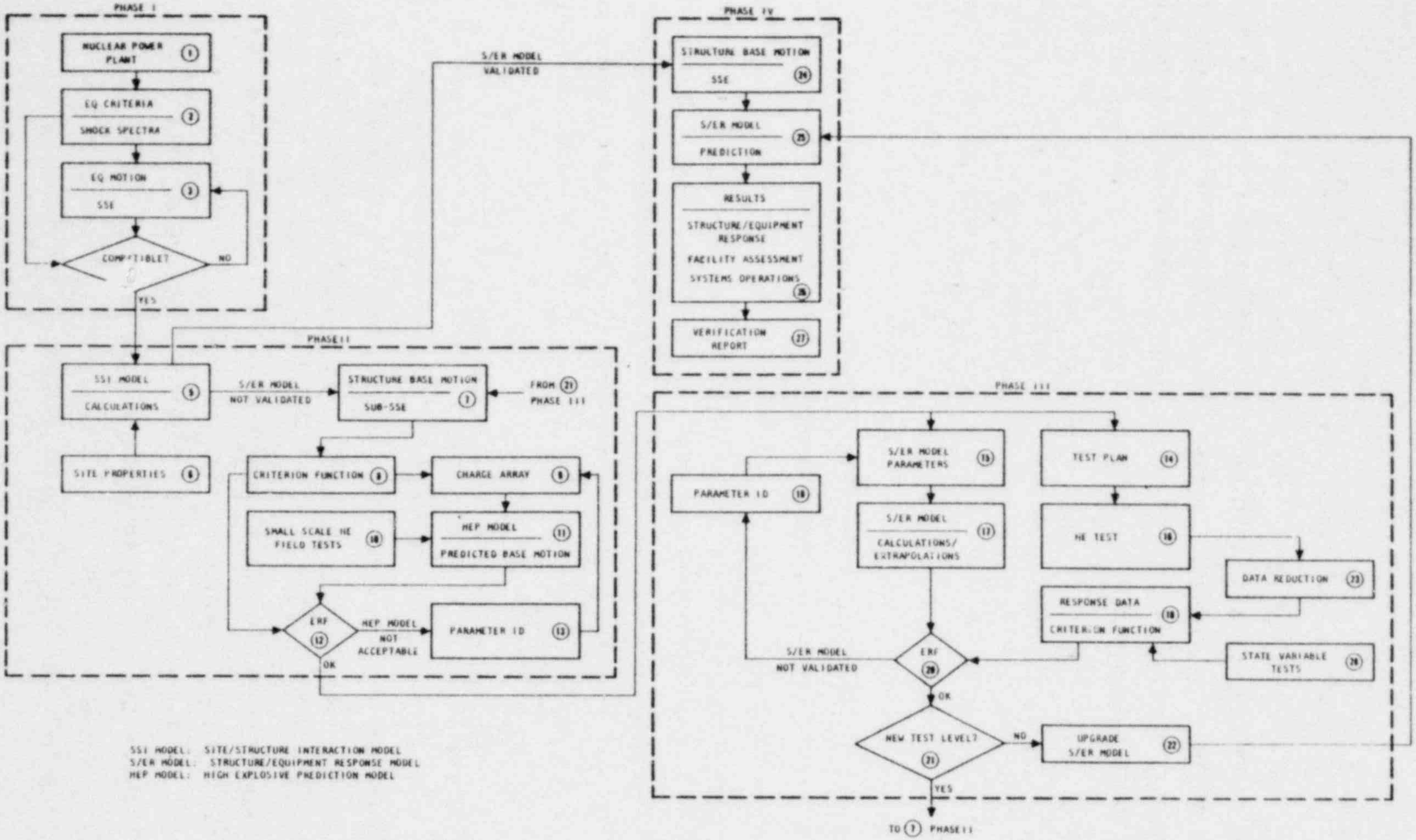


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FIGURE 5-1. EVENT CHART FOR HIGH EXPLOSIVE TEST PROGRAM an earthquake-like motion at the base or foundation of the reactor containment vessels or other structures requiring verification. Thereafter, predictions of the superstructure and equipment responses, either by analytical or experimental means, are correlated to the test data in order to converge to an accurate model. This process is called validation and it is augmented by multiple tests in which the intensity of structure/equipment excitation is varied to help define the effect, classification, and parameters of nonlinear behavior. When the models are validated, the response of the structure/equipment is predicted based on a full SSE environment. This process is called verification and it ultimately results in an assessment of the capability of a reactor facility to achieve a safe shutdown after an SSE.

The procedures presented in Figure 5-1 proceed in four phases. In Phase I, a SSE motion environment must be determined. In Phase II, a simulation environment is generated based on the data from Phase I. The environment selected depends upon the degree of risk that can be tolerated and the enhancement of confidence desired by the plant manager. The validation of the structure/equipment response models is performed in Phase III. Finally, verification of the entire system (with regard to safe shutdown) is presented in Phase IV.

5.1.1 PHASE I: DEVELOPMENT OF SSE FREE-FIELD ENVIRONMENTS

Each power plant site (Item 1 in Fig. 5-1) will have a general earthquake criterion or its particular site-unique criterion (Item 2) defined in terms of an SSE shock spectrum. Each shock spectrum has been generated from a number of sources representing a best estimate of the earthquake threat. However, shock spectra are incomplete specifications of environment because they lack information necessary to relate them to unique motions. While this can be an advantage in design, it is a disadvantage for verification because there are an unlimited number of motions, all different, that can be found to match (within tolerances) the site-unique spectra. Because the structural systems and subsystems are at least somewhat nonlinear, the response of the facility to each of the signatures will all be different, i.e., shock spectra of the responses will all be different. Accordingly, signatures must be found that represent a best estimate of the motion that would be experienced at the site (Item 3). This motion must be compatible (Item 4) with the criterion.

Ultimately, the responsibility to determine this representative motion resides with the utility. For example, it could be an "average" signature, or a statistically acceptable worst case in terms of system response (based perhaps on some simplified analytical models), or it may be a physically realizable upper bound that has the greatest potential for jeopardizing a safe shutdown.

As a starting point, compatible motion-time histories may be generated by the technique of Tsai (1972) to populate the SSE shock spectrum. However, this procedure may be an oversimplification. The earthquake signature may be required to display more specific characteristics of the particular seismic zone in which the reactor is located. Typical earthquakes of this kind have been described by Adham et al. (1979). The utility manager will probably require assistance or consultation to develop appropriate time histories. These motion-time histories should be compatible in amplitude, envelope of peaks, and time duration to be a reasonable representation of earthquake records. The SSE shock spectrum is a conservative prediction as it envelops spectra peaks of probable earthquakes for the site in question. An earthquake that would completely fill the spectrum would be a conservative estimate, and, as such, computable motion-time histories for the SSE spectrum would also be conservative.

5.1.2 PHASE II: DESIGN OF EXPLOSIVE ARRAYS TO SIMULATE EARTHQUAKES

It is possible to place sufficient high-explosive charges in the ground to excite the structure and all of its subsystems to the level of the predicted SSE environment. In Phase II, an acceptable simulated earthquake environment is to be found to which the structures/equipments can be tested. The higher the intensity of the test, the greater the confidence in the test data and the final verification assessment. It is the responsibility of the utility to determine the level of test that should be conducted. The options consist of a tradeoff of risk balanced against increased confidence with cost as a controlling factor.

It is not the intention of the test to actually create an earthquake environment in the free field. The idea is to create an earthquake-like motion of the foundation of the critical structures (Item 7). This should be done via a site/medium interaction (SSI) computer program (Item 5). The result of this analysis is the criterion function (Item 8) for the motions that are to be generated at the base of the structure by the high-explosive charges.

Previous studies have shown that greatly simplified SSI-type calculations may not produce even reasonably accurate results. The work of Chrostowski et al. (1972) illustrates this situation. Recently, their findings have been substantiated by Isenberg et al. (1978). It is recommended that the selection of the model be based on the following guidelines. If, as the result of interaction between the structure and the ground, stresses in the ground would exceed the strength of the medium (or for that matter, the structure), a nonlinear interaction should be conducted. Otherwise, a linear analysis would suffice.

An appropriate model would consist of at least a two-dimensional finite element representation in which the properties of the ground should be expressed in terms of the Lamés constants for elastic systems. For the nonlinear case (or more exactly, the nonlinear, inelastic case), typically, nonlinear, hysteretic stiffness properties are used together with a definition of the yield surface and a flow rule for postfailure behavior. The recent work of Isenberg et al. (1978) illustrates the consequences of using oversimplified SSI models: large errors can be produced by a poor selection of models or model parameters.

The basis for selecting properties is obtained from a site properties investigation (Item 6). Structure base motion (Item 7) should be very carefully performed because there is virtually no corroborating approach to confirm the interaction phenomenon. It must be kept in mind that high-explosives would be used to produce a structure motion. It does not simulate, in all respects, the SSI that would occur in an actual earthquake. This would only occur if the high explosives were used to create a free-field earthquake motion. Thereafter, in the verification sequence, this base motion is considered to be the new earthquake criterion for the test design.

The design of the high-explosive charge array (Item 9) can be undertaken when the criterion function (Item 8) has been determined. The object of the array design is to create the prescribed base motion as inexpensively and safely as possible. The following factors should be considered: (1) the medium will respond nonlinearly to the detonation of buried charges, and (2) a reasonably optimum array must be found in order to approximate the criterion funtion. Nonlinear behavior compounds the difficulty of such an effort. In this connection, it is not necessary that the criterion function be exactly reproduced. It will be acceptable if a reasonable earthquake-like motion can be found. Earthquake-like motion is construed to mean a reproduced signature that has: (1) a shock spectrum that matches the spectrum of the signature in Item 8, (2) comparable duration, and (3) time domain characteristics similar to the criterion function.

The charge array of Item 9 can be designed by utilizing: (1) empirical relationships obtained from small-scale field tests or (2) analytical techniques. Because of the complexity and difficulty of the latter approach, it is not recommended; although if properly handled, it can investigate the interaction among spaced charges in multiple arrays. As a starting point, the empirical approach is preferred.

Item 10 recommends that small-scale field tests be conducted at the specific site. A typical test set up is illustrated in Figure 5-2. A number of small charges are located at various ranges and depths and the signatures of the base slab measured. Various charge weights establish

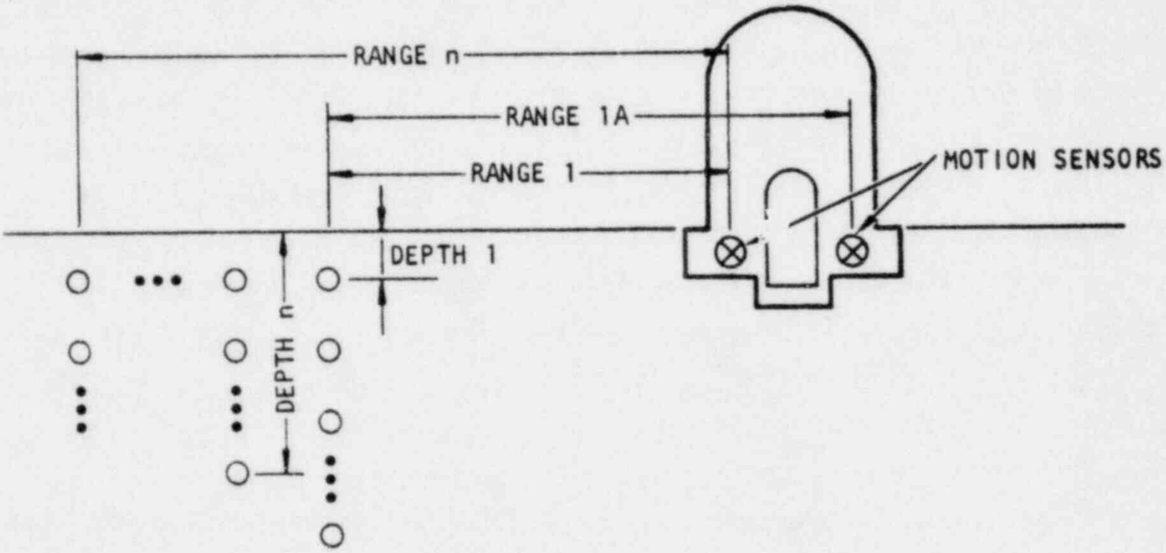

FIGURE 5-2. SCHEMATIC ARRANGEMENTS OF SMALL HE CHARGES

the dependence on charge energy. Guidance for this effort can be obtained by utilizing the cube root scaling law. That is, the time and amplitude scales of a motion measured at one charge weight can be extrapolated to the motion caused by another charge weight by multiplying by the ratio $(W_a/W_o)^{1/3}$, where W_a and W_o are the extrapolated charge weights and the observed charge weights, respectively.

The motions caused by single charges as established in Item 10 can be combined by superposition in accordance with the initial charge array configuration defined in Item 9. Justification for this approach is based first on expediency but it also has a theoretical and empirical basis on the use of the techniques developed by Blouin et al. (1976). The predicted base motion thus obtained is shown in Item 11. By comparing the criterion from Item 8 with the prediction in Item 11, an error function (ERF) can be computed in Item 12. If the error between the goal (criterion function) and the prediction is too large, then a new charge array configuration is chosen in Item 9 and the process repeated. The manner by which the array is reconfigured and new error functions computed is conducted through the parameter identification scheme shown in Item 13. The parameters of the blast model are iterated until a suitable charge array configuration is found. The reader is referred to the Appendix of this report, which describes the procedures of the optimization scheme. Initially, parametric routines should be attempted first.

The parametric scheme must be abandoned in favor of a nonparametric systems scheme for situations where independent parameters cannot be found for the selection process. This would occur in the present situation if an analytical procedure is used to predict the base motion in Item 11. If the model considers nonlinearity and interaction amongst the charge responses, a new solution for each particular array in Item 9 will be required. A nonparametric convergence routine in Item 13 would be required. Such routines are also discussed in the Appendix and in Masri (1976).

5.1.3 PHASE III: VALIDATION OF STRUCTURES/EQUIPMENTS RESPONSE MODELS

The methodology for preparing and conducting the field test can be accomplished after an acceptable charge array has been designed in Phase II. The purpose of the field test (which will be conducted at the sub-SSE level) is to provide data for validating the accuracy of models that are then used to perform the verification of the plant in Phase IV.

The development of the test plan (Item 14) is an independent effort that addresses the specific procedures for setting up and conducting the test, including the criteria and selection of instrumentation and measurement systems. This specialized subject is discussed in Section 6 of this report.

The heart of the Phase III effort is in developing, from test data, the parameters that can be used in the models so that verification can occur. This is shown in Item 15.

Several options exist for proceeding quickly to verifying elements if the response of a structure, subsystem, or equipment is known to be linear or nearly linear. This is best illustrated by an example. Figure 5-3 depicts an arbitrary piece of equipment within a structure. A critical stress point is located at Point 2. Known horizontal motion excites the equipment at Point 1. Since the stress is critical at Point 2, strain gages are installed to measure the bending induced strain from which bending stresses will be calculated. It is assumed that the equipment response remains within the linear elastic range.

If $\ddot{x}(t)$ is the acceleration motion Point 1, and $s(t)$ is the strain response at Point 2 (all occurring as the result of tests performed under Item 16), the transfer function can be calculated in Item 17.[*] In

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[*] In general, the S/ER model is a mathematical representation such as a finite element model. In this case, the model is a computed transfer function.

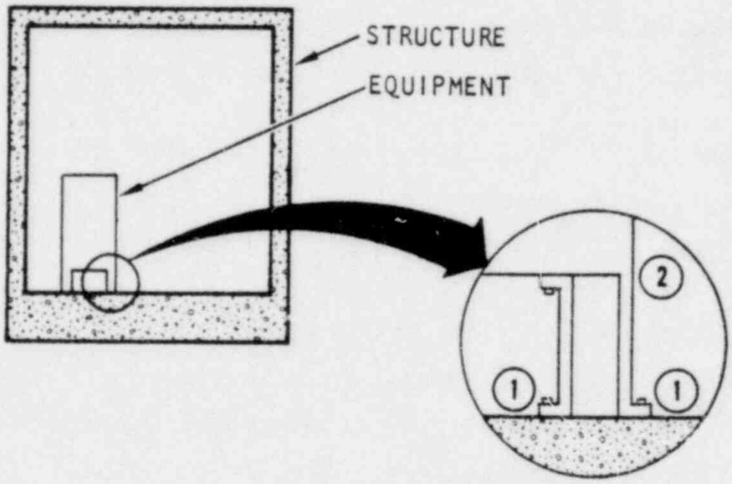

FIGURE 5-3. STRUCTURE/EQUIPMENT REPRESENTATION

another form, acceleration at various locations on the equipment may also be used to form the transfer function. Mathematically, this transfer function is described by:

$$T(\omega) = \frac{S_{out}(\omega)}{\ddot{X}_{in}(\omega)} \quad \text{or} \quad \frac{\ddot{X}_{out}(\omega)}{\ddot{X}_{in}(\omega)} \tag{5-1a}$$

where the notation indicates frequency decomposition via Fourier transformation In the frequency domain for a linear transformation, the ratio of output to input acceleration is also equal to the ratios for velocity and displacement as given in Equation 5-1b.

$$\frac{\ddot{X}_{out}(\omega)}{\ddot{X}_{in}(\omega)} = \frac{\dot{X}_{out}(\omega)}{\dot{X}_{in}(\omega)} = \frac{X_{out}(\omega)}{X_{in}(\omega)} \tag{5-1b}$$

By using a computer program such as PARET, the mode shapes, natural frequencies, and damping can be obtained from Equation 5-1b for a matrix of transfer functions that geometrically map the equipment. Assuming that the mode shapes and natural frequencies remain invariant with respect to the intensity of loading, the predicted response at the full SSE level can be obtained in Item 25 by increasing the damping commensurate with the increased loading which must be considered and included as required. Prediction of the strain-time or motion-time history is accomplished by synthesizing the modal properties obtained from the PARET program (or its equivalent).

Alternatively, if a mathematical model exists or can be developed for the equipment response, the transfer function between the base of the equipment and selected interior points may be convolved with the predicted base motion to estimate equipment response. The transfer function may also be applied to the response spectrum at the base to obtain the response spectrum of the equipment. These methods are discussed in AA (1979b).

The simple example above focuses on important issues that must be addressed in the more general problem. Among these are:

1. How can it be known for sure if the system responds linearly or nearly linearly?
2. If the response is nonlinear, what is the type of nonlinearity?
3. How are the nonlinearities to be considered in the verification?
4. What is the procedure for using the test data to validate the analytical methods?
5. How are the validated analytical methods used to reach the verification assessment?

5.1.3.1 Testing For and Quantifying Linear/Nonlinear Response

The usual practice for performing verification is via mathematical models in which the properties are usually assumed to be linear. If the system is in fact linear and the order of the model agrees with the order of the actual structure, the problem reduces to quantifying the linear parameters for the model. If the system is nonlinear, the problem becomes more complicated because linearized parameters must be chosen to accurately represent the nonlinear phenomenon. Otherwise, a nonlinear analysis can be performed which is technically feasible but more expensive.

Whatever approach is adopted, it is recommended that the parameters be chosen using a state-variable approach. The basic procedure is discussed below, while the approach is detailed in the appendix.

The structures and various equipments and subsystems comprising the facility can be represented by simple differential equations. We assume that no particular problem is encountered in estimating mass. The problem centers on identifying the character of the restoring force where acceleration, velocity, and displacement are measured. Thus,

$$f_i(\dot{x}_r, x_r) = (F_i, m_i, \ddot{x}_i) \tag{5-2}$$

where the restoring force $F_i(\dot{x}_r, x_r)$ is defined in terms of an applied force $F_i(t)$, the mass m_i, and the resultant acceleration $\ddot{x}_i$. The relationship among these parameters involves all of the characteristics of the system including nonlinearities and damping. Equation 5-2 is one of a series of equations obtained from a chained model as shown in Figure 5-4. The notation x_r indicates relative motion between two points, e.g., $x_r = x_2 - x_1$ and $\dot{x}_r = \dot{x}_2 - \dot{x}$.

A load $F_n(t)$ is applied at a particular point n and the response $\ddot{x}_n(t)$ is obtained in order to evaluate the restoring force. Since the mass m_n is assumed to be known, Equation 5-2 can be evaluated (Masri et al., 1979). By a process of coordinate transformations and rearrangement of the data, force-displacement plots as exemplified in Figure 5-5 can be obtained. The plots illustrate the stiffness and damping properties occurring at point n. Figure 5-5 illustrates a typical type of nonlinearity. The hysteresis is related to the viscous damping occurring at the point. The exciting force can be generated by any convenient method, with vibration shakers or pulser devices. This test, identified as Item 28, is conducted independently of the HE test in Item 16.

The importance of this diagnostic-type test bears special attention. If multiple state variable tests are conducted, the nonlinearity and damping can be determined as a function of the level of excitation at various locations in the structures or equipments. These data are directly applicable if nonlinear calculations are to be conducted; they provide guidance to parameter linearizations if linear analyses are performed. However, an even more direct approach for linearizing models can be used as discussed in the next subsection.

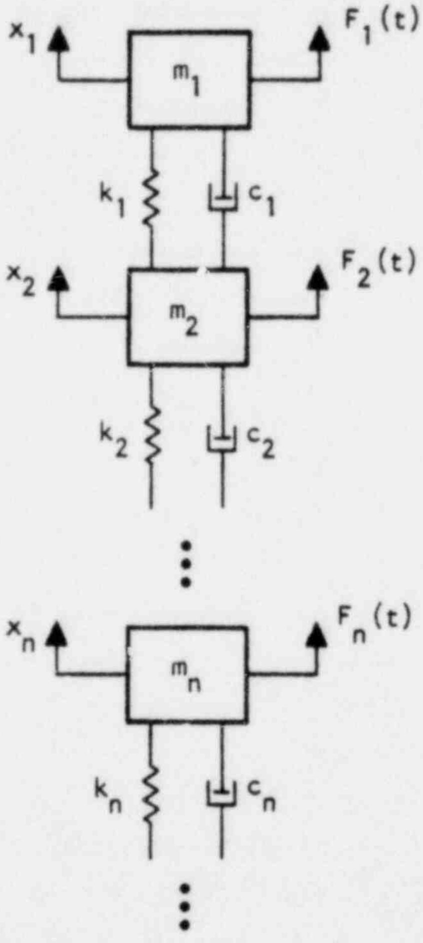

FIGURE 5-4. CHAINED LUMPED PARAMETER MODEL

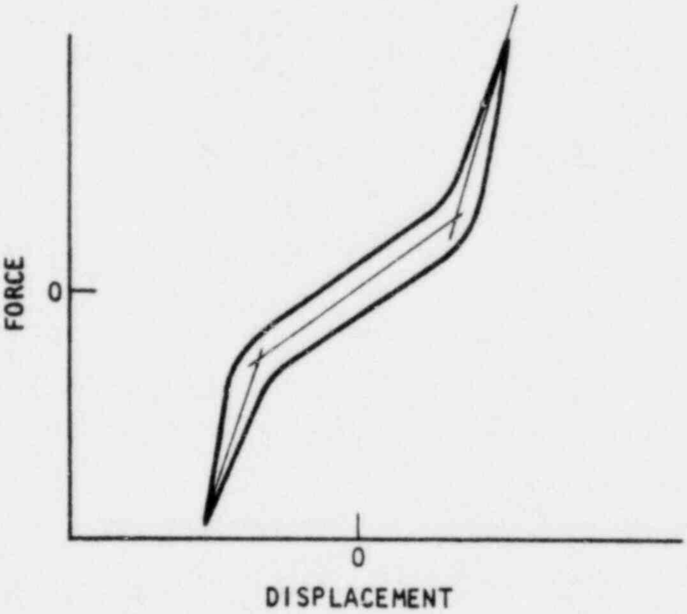

FIGURE 5-5. TYPICAL FORCE-DISPLACEMENT RELATIONSHIP FROM A STATE-VARIABLE TEST

5.1.3.2 Selection of Model Parameters

Satisfactory verification results depend on definitions of model parameters. Referring to Item 15 in Figure 5-1, linear systems require definition of mass, damping, and stiffness. Nonlinear models also require specifications, particularly in nonlinear damping and stiffness. Linearized models, if used, attempt to account for nonlinear behavior by a judicious use of linear parameters. This section addresses this issue.

The transfer function method for predicting response (refer to Eq. 5-1) is applicable if a system is in fact linear, as determined either from a priori knowledge or from a test of the type described in Section 5.1.3.1. Some degree of nonlinearity will exist in many cases even at the sub-SSE level, and an iterative procedure will be necessary to arrive at the proper parameters. Such a procedure also applies to linear systems.

The iterative procedure consists of an initial selection of parameters in Item 15 from which responses are calculated in Item 17. An ERF in Item 20 can be computed by comparing the calculated responses to the measured responses in Item 18. If the ERF exceeds a predetermined level, a new set of parameters is selected in Item 15, and the process is repeated until an acceptable ERF is achieved.

The formality of selecting new parameters occurs in a minimum variance (Bayesian) estimation routine (Item 19) whose details are presented in the Appendix. The technique is amplified in Hart et al. (1977). Basically, however, the routine accepts information from previous calculations and measurements to automatically generate new sets of parameters in order to minimize the ERF. The minimum variance method considers that both model parameters and data have a statistical distribution.

Each selection of parameters applies only to the specific data obtained from Item 18, which is the result of a specific test (stepwise linear parameters). An improvement in the range of parameters of the S/ER model can be achieved by conducting tests at several levels of intensity (Item 21). If more than one test is desired due to nonlinearities, it will be necessary to return to Phase II at Item 7 and perform the subsequent operations as before. When this has been completed, it is then possible to begin the verification work of Phase IV.

The set of procedures that translate the results of a test in Item 16 to reliable test data in Item 18 is an important function that has not been touched upon. Item 23 is the data reduction bridge between raw data and processed data. Data reduction consists of processes to correct aberrant data as well as processes to transform data into more usable forms. This subject is a highly developed one and is tailored to the requirements and problems of a particular study. A number of standard texts have been published on the subject. A specific data processing plan should emerge as one of the efforts to be completed as the specific test plan for a particular reactor is developed. Subjects of especial interest to reactor tests are discussed in the appendix.

5.1.4 PHASE IV: VERIFICATION OF REACTOR FACILITIES

Phase III may reveal that verification accuracy could be improved if more appropriate S/ER models or improved existing S/ER models are used in Phase IV operations (Item 22). This is based on the observed nonlinear behavior of structures and equipments in the state-variable tests in Item 28 in addition to the optimized parameters obtained via the minimum variance operations in Item 19.

The state variable tests of Item 19 in conjunction with the multiple tests conducted in Item 16 provide a basis for estimating the parameters for use in the verification predictions of Item 25. The input to the S/ER models will be provided by the SSI calculation (Item 24) performed for the SSE as an input.

When the S/ER calculations have been completed, the results will be studied (Item 16) with an eye toward assessing the capability of the reactor facility to sustain an SSE and safely shut down. Typically, the results of the program including descriptions of the test procedures and those other activities delineated in Figure 5-1 will be recorded in a report or series of reports (Item 27). Dissemination of these reports would greatly assist other plant managers and investigators to more easily perform their tasks at other sites.

5.2 SIMULATION OF EARTHQUAKE-LIKE MOTION USING PULSER TECHNIQUES--STRUCTURES AND SYSTEM TESTS

Pulser devices are strategically located on major structures to force the structure to respond in an earthquake-like manner. The aggregate energy of a system of pulsers is less than that available with high explosives. Accordingly, less mass of the structure can be mobilized and the magnitude of motion will not be as great. However, this does not invalidate the optimization of parameters for mathematical models; it only increases the uncertainty of extrapolating these parameters to full SSE levels. However, the test is especially well suited to driving the superstructure and all equipments and subsystems attached thereto. Moreover, the pulser approach provides greater control over the simulated environment because the soil is not directly included in designing the test apparatus. The procedures associated with pulser tests are similar to those discussed in Section 5.1 for high-explosive testing. As before, the test data are used to validate analytical models which are then used to verify superstructure and subsystem response at full SSE levels.

The procedures for performing pulser tests of this nature occur in four phases, as depicted in Figure 5-6. Phase I consists of a selection of the SSE free-field environment. A simulation environment is generated in Phase II. Phase III is concerned with validation of the analytical models based on data obtained from the test. Verification of the structures and the subsystems is conducted in Phase IV.

5.2.1 PHASE I: DEVELOPMENT OF SSE FREE-FIELD ENVIRONMENTS

The effort required in this phase is identical to that discussed in Section 5.1.1.

5.2.2 PHASE II: DESIGN OF PULSER ARRAYS TO SIMULATE STRUCTURE MOTION

The current state of the art (and perhaps an inherent limitation) of pulser technology precludes the possibility of exciting a containment structure to full SSE environments or even to magnitudes approaching this level. Even structures somewhat less massive, such as those housing electrical generators or control and monitoring systems, may be limited in their magnitude response. The duration of the earthquake motions is a primary problem in sustaining high-level excitations; the pulsers cannot, in the present state of development, store sufficient energy to produce large motions for extended periods of earthquake motions although long durations can be achieved if the force requirements are relaxed.

The reduction in power (or alternatively, the reduction in force on the structure) reduces the risk of damage to the structure; it also places a heavier burden on the analytical techniques ultimately used for verification. Even so, the pulser device is a marked improvement over other devices used for testing because it excites a structure to an earthquake-like motion, containing the frequency distributions and durations inherent in earthquakes.

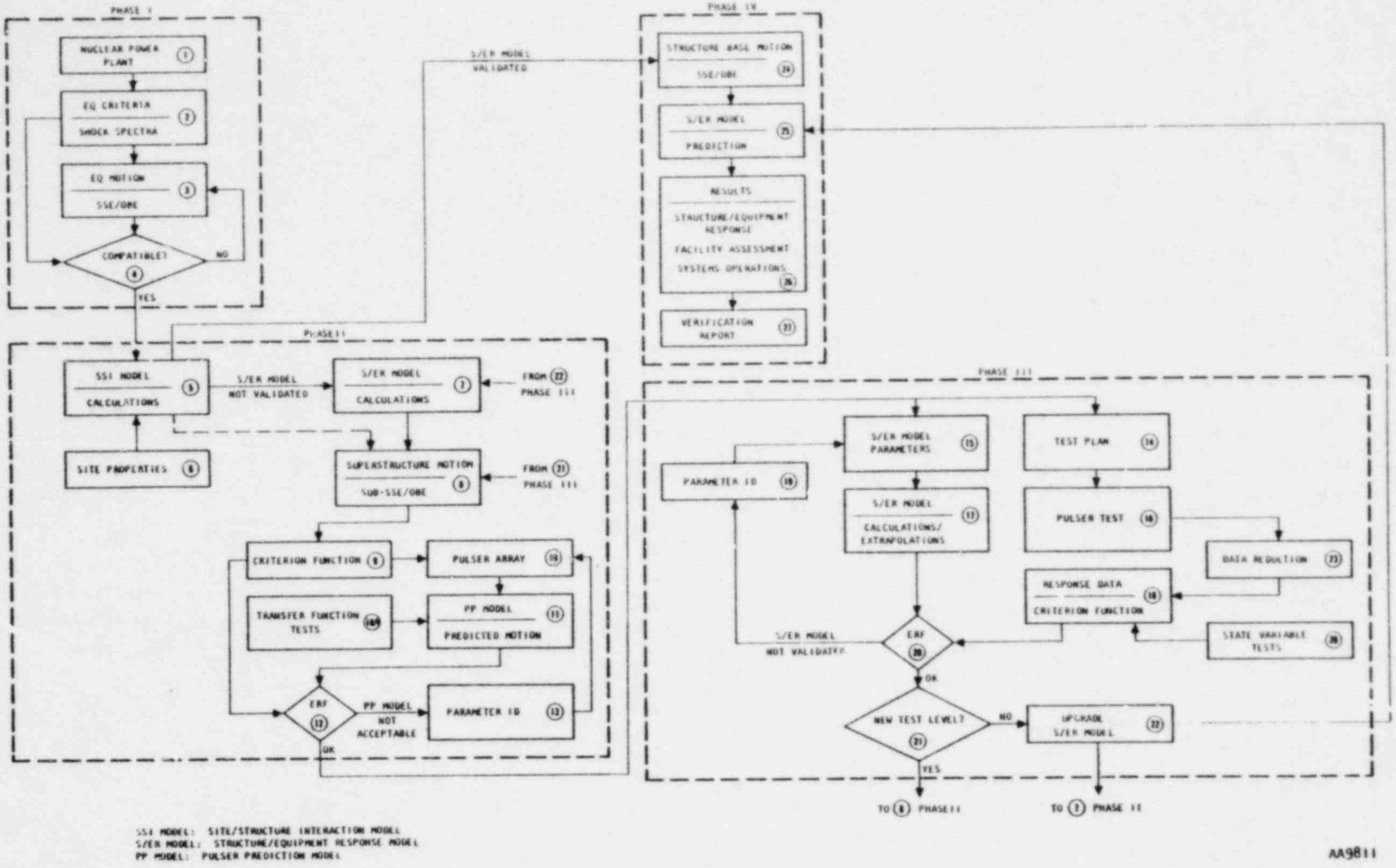

FIGURE 5-6. EVENT CHART FOR PULSER TEST PROGRAMS: STRUCTURES AND SYSTEMS

Figure 5-7 shows a typical arrangement of gas pulsers mounted directly on a containment structure. In practice these devices may be supported by scaffolding or they may be mounted in a stand-alone fashion as shown. Alternatively, other types of pulsers may be used. Whatever its form, the devices apply a series of forces to the structure. In the aggregate, they cause the containment vessel to respond according to a specified schedule of motion. Phase II provides a definition of the schedule and spells out how the pulser system is designed to achieve the desired response.

The event chart in Figure 5-6 is very nearly the same as that shown in Figure 5-1 for the high explosive test. A very carefully executed site/structure interaction calculation (Item 5) will be required to develop the structure base motion. This calculation is identical to the one described in Section 5.1.2. The model will require a large number of degrees of freedom to represent the medium. The usual practice is to limit the definition of the superstructure and the internal subsystems so that the SSE calculation can be performed efficiently. Nevertheless, sufficient detail of the containment vessel response within the frequency domain of an earthquake may be produced in Item 5 so that it may be possible to progress immediately to Item 8. This path is shown as a dashed line in Figure 5-6.

In the more general case, however, a separate containment vessel analysis (Item 7) would be required. Since mathematical models for this type of structure are used in the normal course of verification anyway, this step requires little additional effort and it should be performed. The superstructure motion in Item 8 becomes the criterion motion in Item 9 for the pulser array that occurs in Item 10. An alternative method is given in the appendix. in which measured system functions are used to directly compute motions.

The energizing of the pulser array will result in a response of the structure. It is necessary to predict beforehand whether this response satisfactorily matches the criterion motion. This can be accomplished in either of two ways: (1) by developing a mathematical model (which could make use of the S/ER model) or (2) by measuring the transfer functions between the

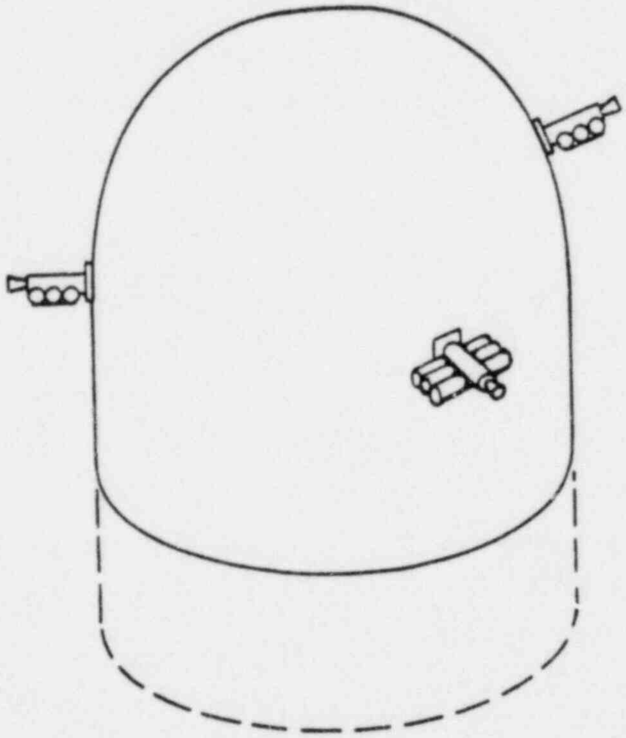

FIGURE 5-7. ARRANGEMENT OF GAS PULSERS ON A CONTAINMENT VESSEL

points where force is applied and motion is desired. The latter applies if the system is linear; the former applies regardless of the mode of response. The choice depends on the characteristics of the particular structure. Either method of prediction is termed the Pulser Prediction (PP) Model in Item 11.

As an illustration, a mathematical model of a structure is shown in Figure 5-8. If the structure is required to respond with, say, n motions at n masses, then n forces or less will be required, not necessarily at the same points where the desired motion occurs. By the proper selection of the F_n forces, the x_n responses can be obtained. The procedure is described in the Appendix. In Figure 5-8, the R_n terms are the restoring forces. They need not be linear.

If transfer functions of the structure are to be obtained, they would be performed with separate tests (Item 10A) using shakers, pulsers, or any other convenient apparatus. The transfer function data would then constitute the PP model in Item 11.

The purpose of the parameter identification scheme in Item 13 is to design a pulse array system in Item 10 that would allow a suitable match between the criterion function in Item 9 and the predicted motion in Item 11 as determined by the error function in Item 12. Parameter optimization means that the parameters of the model are iterated or the transfer functions are scaled and used to design the array.

5.2.3 PHASE III: VALIDATION OF STRUCTURES/EQUIPMENT RESPONSE MODELS

The procedures of Phase III proceed as discussed in Section 5.1.3 for high-explosive testing.

5.2.4 PHASE IV: VERIFICATION OF REACTOR FACILITIES

The procedures of Phase IV proceed as discussed in Section 5.1.4 for high-explosive testing.

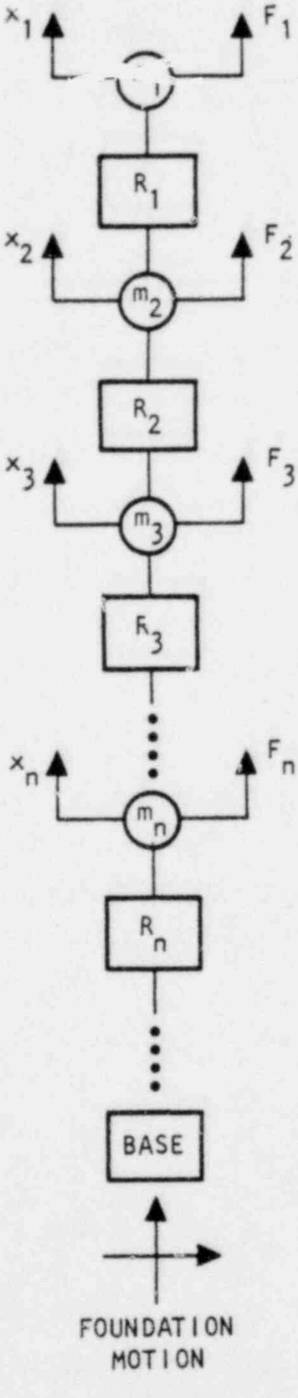

FIGURE 5-8. TYPICAL REACTOR STRUCTURE MODEL

5.3 SIMULATION OF EARTHQUAKE-LIKE MOTIONS USING PULSER TECHNIQUES--EQUIPMENT AND SUBSYSTEM TESTS

When high-explosive or major pulser tests cannot be applied to large structures or major systems, a test of reduced scope may be indicated. This type of test will usually be conducted within the interior of the structures and will be applied directly to equipments or to subsystems that require verification. The pulser test applied in this way is very similar to the procedure described in Section 5.2.

The procedure that may be applied in Phase II to design pulser systems for performing a validation test involves testing the equipment or subsystems in place. In this procedure, the interaction effect of equipment and structure is included in the test.

5.3.1 TESTING WITH EQUIPMENTS OR SUBSYSTEMS IN PLACE

The procedures for performing pulser tests in conjunction with mathematical models are illustrated in Figure 5-9. Again, the procedure is divided into four phases: Phase I is the selection of the SSE environment; Phase II is the environment of the equipment or subsystem support point and of the equipment itself; validation of the analytical models or rationale for extrapolation of test data are covered in Phase III; and the final verification of the tested element occurs in Phase IV.

5.3.1.1 Phase I: Development of SSE Free-Field Environments

The effort required in this phase is identical to that discussed in Section 5.1.1.

5.3.1.2 Phase II: Design of Pulser Systems to Produce Localized Motions in Reactor Structures

Pulsers installed directly on equipments, systems, or subsystems are intended to excite these elements that attach or mount directly to the parent structure to match predicted or specified earthquake motions.

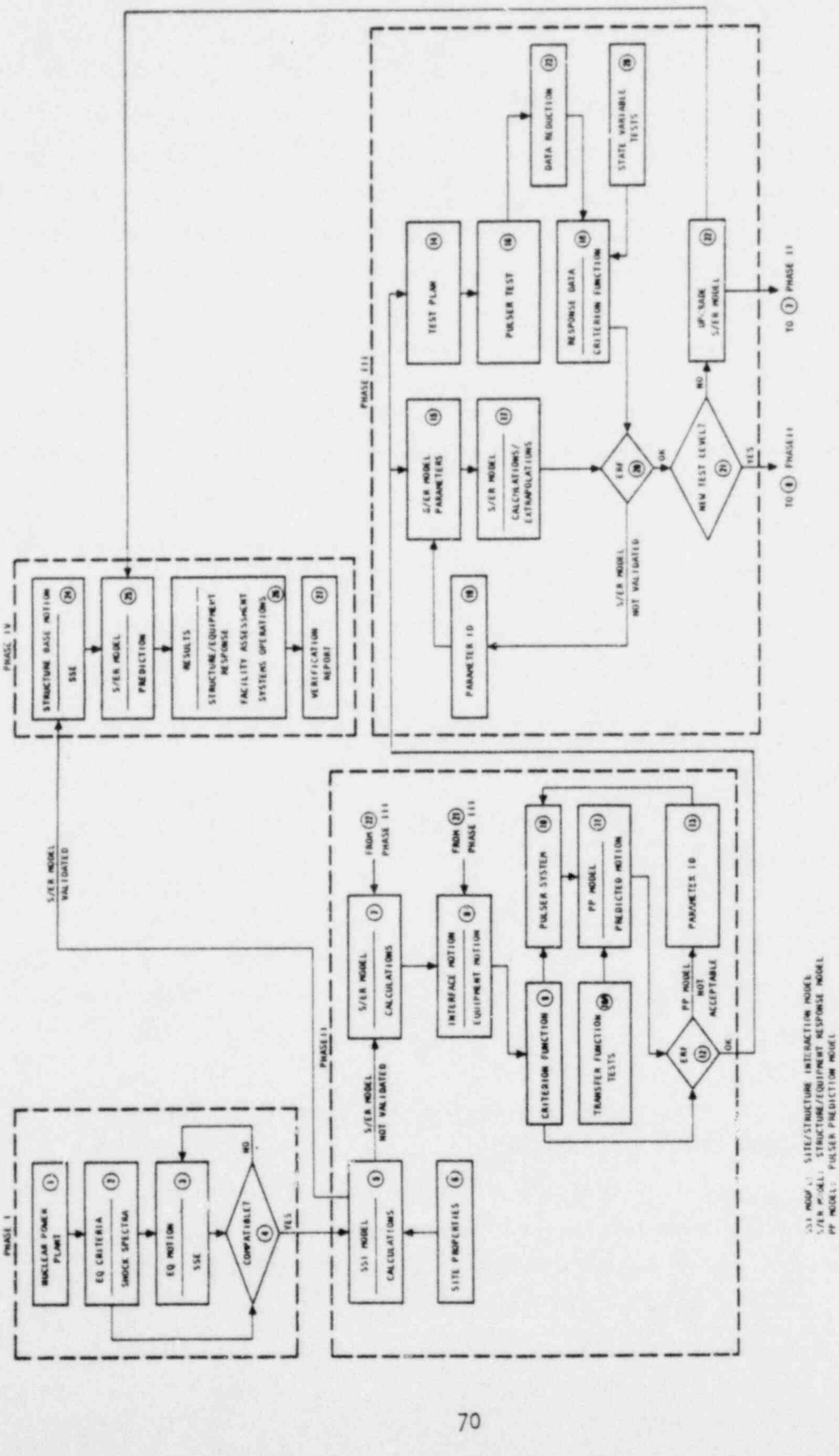

FIGURE 5-9. EVENT CHART FOR PULSER TEST PROGRAMS: EQUIPMENT AND SUBSYSTEMS TESTED IN PLACE

Figure 5-9 shows that the environments computed for this type of test come about as the result of performing SSI calculations (Item 5) in connection with structure/equipment interaction analyses (Item 7). Unlike Figure 5-6, in which there is a possibility of ascertaining structure motion directly from the SSI calculation (i.e., in progressing directly from Item 5 to Item 8), this shortcut is not viewed as reasonable, because it is desirable to specify the motion at the attach point and on the equipment with as much accuracy as possible. Thus, Item 8, the calculation of this interface motion, is reached only by progressing through Item 7.

Alternatively, the structure/equipment interface motion and equipment motion can be determined from motions predicted in Item 25 of Figures 5-1 or 5-6 where these responses were determined from previously performed high-explosive tests or pulser tests on structures.

When the equipment motions in Item 8 have been determined, they become the criteria functions in Item 9. The pulser system developed in Item 10 subsequently is designed to match the criteria motions. A pulser prediction model in Item 11 provides a basis for the design of the pulser system. This model may be mathematical or it may use transfer function data obtained from transfer function tests performed in Item 10A. If the systems behave nonlinearly, the use of transfer functions (Item 10A) in the model of Item 11 will not be valid. In that case, mathematical models will be required. When the pulser array adequately produces the criteria motions as determined in the error function test (Item 12), Phase II is complete. Otherwise, the pulser array must be iterated (Item 13) and the logical processes repeated until the pulser array computes the desired responses. When the pulsed responses match the criterion function, the pulsers are programmed accordingly, and tests may be conducted. For all intents and purposes, this approach to the performance of Phase III corresponds directly to the discussion presented in Section 5.2.2 for testing large structures and major systems.

5.3.1.3 Phase III: Validation of Equipment/Subsystem Response Models

The procedures of Phase III proceed as discussed in Section 5.2.3 for pulser testing of major structures and systems.

5.3.1.4 Phase IV: Verification of Reactor Facilities

The procedures of Phase IV proceed as discussed in Section 5.2.4 for pulser tests of major structures and systems.

SECTION 6

TEST PLANNING

Each plant will require a formal test program to support a verification plan that satisfies the unique requirements of that reactor plant. This section presents guidelines for the preparation of those test plans. Because each plan will have an individual character, these guidelines are not meant to supplant the test plan itself. Rather, they are intended to point out specific factors that should be considered as related to reactor plant verification.

6.1 BACKGROUND

A test plan is a detailed description of methods used to create an environment to test a system and to measure the system responses of a specified stimulus. The system to be tested may consist of an entire power plant, a containment or other critical structure, or the equipments contained within such structures. The plan may consider a single test or a whole series of tests. The method for writing the plan relies on principles that are independent of the scope of the test program itself.

A test plan is prepared by a central coordinator who coalesces information obtained from an organization and a variety of sources. It represents the combined expertise of these sources to produce documented procedures that ensures the successful execution of the test. The plan addresses first and foremost the question of how the acquired data is to be used. Thereafter, the detailed explanations of the specific type of data to be obtained and the amount of data necessary to support the verification must be specified. In general, the preparation of the plan proceeds from the general to the specific. Throughout, three questions must be kept in mind:

1. What is to be accomplished in the test?
2. Why is the test being performed?
3. What are the success criteria of the test?

The answers to these questions are discussed below.

6.2 ANALYST/EXPERIMENTALIST RELATIONSHIP

The experimental data satisfy the verification program in one or more of the following ways: (1) the data are to constitute a direct proof test of elements of the plant, i.e., parts of the facilities are to be subjected to the criteria SSE threat, (2) the data obtained from a sub-SSE test are to be scaled to the full criteria levels, and (3) the data are to be used to validate mathematical models which will in turn be used for verification. The latter approach is the most common application of test data. It obviously requires close coordination between the experimentalist and the analyst.

The analyst generally specifies the form and characteristics of experimental data that should be obtained so that it can be correlated to the analytical data. The experimentalist then designs the test program to satisfy those requirements. If the data are to be used as a proof test or a partial proof test (where data would be scaled directly to criterion levels), the experimentalist plays a more prominent role. The mathematical models still play an important role in defining where instrumentation should be placed and what level of response should be expected.

Based on the interchange with the analyst, the experimentalist will have an understanding of not only what should be recorded or witnessed but also the relative criticality of each observation. Thus, he is in a position to decide upon the level of redundancy that is desired to reduce the risk of losing critical data if sporadic recording system malfunctions occur.

6.3 TEST REQUIREMENTS

Previous sections have dealt with the procedures required to generate an earthquake-like motion for the free field, at the foundation of the power plant structure or at the attach point of equipments. These procedures have considered the theoretical aspects and the methodology which is used in evolving the desired time history of input. The test plan translates these theoretical considerations into detailed plans so that tests can be designed and conducted.

6.3.1 TESTING OPTIONS

The high-explosive test is the most direct method to achieve validation of analytic models because the structures and equipments are all tested at once and with their proper interactions. The direct stimulation of critical structures using pulsers on the exterior of structures requires a more limited source of energy and results in a more limited response motion. The use of pulsers directly on internal equipment requires even less energy but does not necessarily produce less response motion since favorable force-to-mass ratios may be obtainable. The selection of the test method is the decision of the utility manager and his consultant staff.

6.3.2 DESIGN OF TEST

If high-explosive tests are selected, the explosive array geometry, the weights of charges, and the sequence of detonation are factors to be considered. These factors lead to other considerations: the method of drilling placement holes, the actual procedure of placing the high explosives in those holes, the design and implementation of the control and firing systems, and the development of the safety plan considering the general area, the equipment, and the impact on the environment.

If pulser tests are selected, and mechanical, gas, steam, or chemical devices are used, the physical design and the attachment scheme as well as gas or steam storage and ignition systems for chemical devices must be considered. Safety considerations must always be given careful thought and although the pulser devices contain less energy than high explosives, the tests may be conducted on site in an operating environment, and this tends to complicate test procedures somewhat.

6.3.3 MONITORING TEST PERFORMANCE

Whatever test method is chosen, it is necessary to devise procedures for determining whether the test meets it objectives. Special measurements can be made to monitor test performance. For high explosives, instrumentation will be required to determine if the detonation sequence and timing occurred as projected. The close-in stress, local accelerations, and spectra of the acceleration at the foundations must be monitored to determine if criteria were satisfied.

Special instrumentation should include an array of sensors between the explosives and the structures under test, in order to define at the interface of the geological medium and the foundations of the various structures the wave front characteristics generated by the explosives. The wave velocities or other means of determining changes in geological properties should be measured to ascertain the effect on stresses caused by the first, second, third, or higher order series of explosions in the same area.

If steam pulsers are to be used, the water temperature, chamber pressure, local thrust level developed, valve actuation times vs. thrust, and thrust vs. chamber pressure should be recorded. Similar measurements will be required for cold gas pulsers or for chemical pulsers. When mechanical devices are used, the impact velocity, the force generated, and the spectra of the force pulse also must be recorded.

Spatial arrays of pulsers installed on the structures will require that the sequence of operation and the input force time histories be measured. From these data, comparisons will be made between actual time histories and the predicted time histories. Similar information should be obtained for pulsers used on individually excited equipments whether they are tested on site or removed for off-site testing.

Measurement systems used for system diagnostics will also have different requirements than those for the response measurements. Higher data sampling rates and larger frequency bandwidths of the structures will ensure that either undesirable test characteristics were not produced or, if they were, their magnitudes will be known.

6.3.4 CONTROL OF ENVIRONMENTS

When high-explosive testing is performed, certain safety and liability requirements must be taken into account. The ground motion generated by an explosion will not only excite the reactor structures but will exit the boundaries of the nuclear power plant site unless properly controlled. In order to evaluate how much energy is "escaping," instrumentation should be installed at the property lines and at structures in the vicinity.

Some pulsers produce noise, and their sound levels should be recorded pretest, during test, and posttest at locations near the property line or at locations of substantial personnel habitation. Separate photographic coverage, both still and cinematic, should be provided to establish the physical characteristics of the test, e.g., whether venting of charges occurred or whether projectiles were formed as the result of the test.

Many potential problems can be mitigated by controlling back-scatter from the explosions by means of trenching or buffering near the charges. Where necessary, pulsers should be muffled or warnings broadcast to alert the citizenry adjoining the site that testing will take place.

6.4 SYSTEM RESPONSE REQUIREMENTS

The analyst, using his mathematical models, plays a key role in assisting the test conductor to select and install instrumentation to measure structure and equipment response. The models predict the expected modes and the amplitudes of response. In any test, an unlimited array of instrumentation will guarantee that sufficient measurements will be made to define how the system responded to the test. However, cost constraints always severely limit the instrumentation, so the proper placement of the available sensors is a critical constraint. For example, care must be exercised to ensure that motions will not be monitored at points of minimal response. Moreover, the degree of single-axis or multi-axis response must be ascertained since complex motion is likely to occur. From these studies, determination also will be made of the bandwidth required for the transducers and the systems. One of the factors to be considered when selecting techniques and transducers is the bandwidth of the transducers themselves. AC coupling tends to eliminate some of the very low frequency problems associated with DC systems.

In general, the use of arrayed measurements is a desirable and necessary consideration because it affords a degree of redundancy without duplicating measurements at a given point. A properly designed array ensures that a malfunctioning transducer does not result in a total loss of data since adjacent transducers can be used to interpolate the response at the point where data is lost.

6.5 INSTRUMENTATION SYSTEM REQUIREMENTS

Data acquisition has been greatly assisted in recent years by the economical use of computers in instrumentation systems and testing procedures. Computerized acquisition systems provide such services as look-up tables for transducer calibrations, and they prompt the experimentalist to properly sequence calibration and data acquisition activities. Computers also assist in formatting data so that it is readily correlated to analytical data obtained from mathematical models.

6.5.1 INSTRUMENTATION INSTALLATION

Depending on the relative size of the test object and the sensor to be mounted to it, consideration must be given to the way in which the transducer is installed. The transducer may be bolted directly to the test structure or it may be bonded with any of several suitable adhesives. Care must be exercised that the attachment method does not cause an undesirable secondary response characteristic.

The manner of routing cables between the transducers and the central recording station is also a factor. Cable routing and attachment methods must not present a hazard to personnel but they should provide a secure, economical, yet temporary installation.

6.5.2 DATA PROCESSING SYSTEM

In order to facilitate a one-to-one comparison with analytical models, the processing system should format the experimental data so that it is easily compared to predictions. This may be done on a resident computer in the data acquisition system or at a remote computer facility. The remote facility may either be accessed by time share systems or by a batch input terminal.

Not only is the final data of importance here, but it is equally important to consider the quick-look capability to evaluate the success of the testing while it is in progress. Time histories of all the channels plus Fourier spectra and the transfer functions are desirable formats for evaluating the quality of the data.

6.5.3 DATA ACQUISITION SYSTEMS

The data may be recorded either in an analog or a digital mode or sometimes in a combination of both. If at all possible, it is preferable to record in the digital mode to facilitate speedy use by the analyst. If the data nave been recorded in an analog format, the data processing system must convert it to a digital format for subsequent computer processing. The special requirements of analog-to-digital conversion must be considered if this mode of operation is used.

The manner in which data is recorded depends on the total number of channels, the types of sensors, the bandwidth required, the digitization level, the maximum throughput rate, the length of each test record, and the sampling rate required. The signal must be conditioned to provide uniform ranging into the analog-to-digital converters based on the digitization level selected. If a high digitization level is selected, say, 14 to 16 bits, then high quality amplifiers (high linearity and stability) must be used. If a lower digitization level is used, say 10 or 12 bits, then the linearity requirements in the amplifier and the cost are both reduced.

For high-explosive tests, two or more systems will probably be used operating at vastly disparate sampling speeds. The high-speed data system (on the order of thousands of samples per second) will be required for the source diagnostics, while the low-speed sample rate (on the order of tens of samples per second) equipment will record the structure responses.

6.5.4 PHOTOGRAPHIC AND VIDEO RECORDING REQUIRMENTS

Documentary photography as well as scientific photography will provide quantitative evidence of the tests. High-speed cinematography coverage appropriate to the test operation as well as video disk or single-frame playback from video tape recordings of the events should be considered. Prompt and adequate coverage of many aspects of the testing by means of still photographs, both black and white and color, should be included.

6.6 TEST MANAGEMENT AND CONTROLS

In addition to the technical subjects covered above, a test management plan will also be developed. The plan should include logistics for conducting the test, the control and procedures for documentation, staffing requirements, and preparation and control of time, schedules, and costs.

Of special interest will be the logistic support for planning and implementation of the tests. Because the tests must be conducted on site, the test preparation and execution must be integrated within the existing plant operating routines. Factors to be considered are the electrical power requirements, office space, and space requirements for accommodation of instrumentation cables, earth moving or drilling equipment, and access required for the explosive emplacement activities, as well as other environmental and safety aspects.

SECTION 7

PROCEDURE FOR SELECTING INSTRUMENTATION AND MEASUREMENT SYSTEMS

The technology of instrumentation and measurement has reached an advanced state of development. A short treatise only begins to summarize the general knowledge that is available. However, it is possible to address specific issues as related to the testing of reactor facilities. Before embarking on that task, it is worthwhile to mention some of the noteworthy standard works on general applications.

Stein (1969), in recent times, treated measurement engineering as a separate discipline and his text is noteworthy. McGrab (1971) adopts a somewhat more sophisticated engineering approach to the same subject. Doeblin's book (1975) is now in its second edition and is also a worthwhile reference. Two books on grounding and shielding, one by Morrison (1978) and another by Ott (1977) are highly recommended for the importance that those specialties hold in achieving good noise-free data. The book by Mandel (1964) is a clear and highly applicable text on statistical evaluation of experimental data.

7.1 GENERAL CHARACTERISTICS

A helpful contribution to the selection of transducers can be achieved by presenting a chart defining important characteristics of selected transducers. These charts may be expanded by the reader by adding other makes or models of transducers with their appropriate characteristics and specifications. These charts, showing transducer characteristics, provide a guide to select specific transducers for the measurement of specific parameters. The charts are not, nor were they intended to be, inclusive of the transducer market. They do reflect, however, experience with most of these gages in ground-motion experiments at the Nevada Test Site.

This section also includes guidelines for making selections in assembling an instrumentation system. Much of the reference material and many of the recommendations are fully applicable to pulser testing.

7.2 TRANSDUCER CHARACTERISTICS

Four transducer types compose the candidate instruments for measuring reactor facility response. They are accelerometers, velocity gages, displacement gages, and stress gages. The strain gage is treated as a variation of the displacement gage. Each of these transducers is discussed below.

7.2.1 ACCELEROMETERS

Accelerometers can be divided into three categories. First is the piezo-electric device which generates its output by shear deformation of a crystal element. These accelerometers can be miniaturized and are sensitive to small motions. A second gage uses one or more strain gage elements as the sensing device. The strain gages can be of conventional bonded or nonbonded types as well as a bonded semiconductor type. The output of these gages is generally lower than the other categories. The third category is the servoaccelerometer which keeps an inertial mass in a fixed position relative to the case and monitors response through the use of appropriate sensors, a feedback amplifier, and position in a coil. The output of the gage is achieved by monitoring the current required to hold the mass fixed. These three categories are shown on Table 7-1 along with their various specifications.

TABLE 7-1. ACCELEROMETER CHARACTERISTICS

Manufacturer and Model No.	Sensitivity, MV/MG	F.S./Limit, G	Cross Axis Sensitivity, G/G	Damping P.U. Crit	Bandwidth, Hz → Hz	Excitation Required, V	Serious Limitation
ENDEVCO 5241	0.8	10/1000	0.03	None	0.2-2K	30	Undamped
ENDEVCO 2265-20	0.03	20/60	0.05	0.05	0-200	10	Small Physical Size Undamped
KISTLER 303T	10	1/100	0.002	0.07	0-120	28	

7.2.2 VELOCITY GAGES

Three velocity gages are recommended for measuring facility response. The first type (for example, the Trans-Tek and the Schaevitz) develops an output voltage as the result of relative motion between a coil and an inner magnetic core. The second type is an over-damped accelerometer developed by SRI in the 1950s and improved in the mid-1960 (later manufactured by Sparton S.W.). Integrating an accelerometer output signal electronically is commonly tried but requires care in installation since it is prone to baseline error as the result of tilting in the gravitational field. A recent study has examined the installation of velocity gages in a soil medium (Balachandra et al., 1976). Characteristics of velocity gages are presented in Table 7-2.

TABLE 7-2. VELOCITY GAGE CHARACTERISTICS

Manufacturer and Model No.	Sensitivity, MV/in.	F.S./Limit, In./Sec	Cross Axis Sensitivity, G/G	Damping P.U. Crit	Bandwidth, Hz → Hz	Excitation Required, V	Limitation
TRANS-TEK 113-000	500	1000/1000	--	--	200	None	±2" Stroke Limit
SCHAEVITZ VT-Z	600	800/800	--	--	200	None	±0.5" Stroke
SPARTON S.W. 603	9 in./KHz	36	--	--	74	--	FM Output, Special Equipment

7.2.3 DISPLACEMENT GAGES

A number of displacement gages have been developed. Among these are (1) the capacitance type, (2) the eddy-current generation type, (3) the linear variable differential transformers (LVDTs), (4) liner potentiometers, (5) incremental encoders, (6) double-integrating accelerometers, and (7) moving inductance coil types. Characteristics of some of the LVDT type are summarized in Table 7-3.

TABLE 7-3. DISPLACEMENT GAGE CHARACTERISTICS

Manufacturer and Model No.	Sensitivity, MV/0.001	F.S./Limit, in.	Cross Axis Sensitivity	Damping P.U. Crit	Bandwidth, Hz → Hz	Excitation Required, V	Serious Limitation
TRANS TEK 242-000	6.4	0.25/0.375	NA	NA	0-3.6K	6	Mounting Methods
SCHAEVITZ PCA-220	6.0	0.10/0.140	NA	NA	0-250	3	Limited Stroke
SCHAEVITZ HR SERIES	6.3-0.1	±0.5→±10.0	NA	NA	0-250	6	Attachment Methods

Strain gages are considered to be variations of displacement gages since strain is the differential displacement normalized to a gage length. Thus, strain of soil, rock, or concrete can be obtained from measuring displacement. An exception is the bondable strain gages which are used on metals or on rebar in concrete structures.

7.2.4 STRESS GAGES

Stress gages are usually used in soils or rocks especially to measure the interface stress between a structure and the surrounding soil. The gage is about 2 in. in diameter and 1/4 in. thick. Sensing is done by measuring the strain experienced by a relatively thick diaphragm used as one side of the gage. The rest of the gage structure is very stiff and protects the diaphragm from edge loading effects. Semiconductor strain gages are used for increased output.

The most significant work in the development of stress gages has been conducted at the Waterways Experiment Station in Vicksburg, Mississippi (Ingram, 1968). An ongoing program of development has resulted in commercially produced units which have seen wide application, although they have been prone to uncertainties and biases as a result of installation technique. A recent study (Balachandra et al., 1978) addresses installation techniques. Some characteristics of stress gages are presented in Table 7-4.

TABLE 7-4. SOIL STRESS GAGE CHARACTERISTICS

Manufacturer and Model No.	Sensitivity, MV/psi	F.S.Limit, psi	Cross Axis Sensitivity, psi/g	Damping, P.U. Crit	Bandwidth, Hz → Hz	Excitation Required, V	Serious Limitations
Kulite Semiconductor Prod. LQ-080U-3000-X	0.300	3000/6000	0.1	None	0 - 5K	10	Installation Problems of Coupling to Soil
Kulite Semiconductor Prod. LQ-080U-200-X	0.275	200/500	0.03	None	0 - 2K	10	Installation Problems of Coupling to Soil

7.3 GUIDELINES FOR ASSEMBLING A MEASUREMENT SYSTEM

Signals obtained from transducers are routed to recording systems via cables. Specifically, the transduced lead is connected to a multi-conductor cable (or harness) which then enters into an amplitude changer and progresses sequentially to an anti-aliasing filter, a multiplexer, an A-D converter, and finally onto tape or disc. Once on the tape or disc, the signal is then routed to a Fourier analyzer for evaluation. In modern-day systems, a computer controls the flow of data.

7.3.1 CABLE SYSTEM

Transducer cables may pose a special problem when working close to the source. If violent motions occur (for example, across isolation systems or in soils), considerable difficulty can be experienced in maintaining integrity of the cable. In free-field applications, special armored down-hole cables used by oil-well drilling crews can often be used. If the gage is located in hard rock or at the interface between soils and structures, even armored cables may be severed by the relative motion. It is not anticipated that these problems will be commonly encountered in verification testing of reactor facilities.

For general applications, multi-conductor cable used by the telephone company is an adequate and inexpensive source. It should be kept in mind that installation costs are often based on the unit length of cable, whether the cable has 300 pairs of conductors or a single pair. Thus, cable harnesses should be used in those areas where an array of measurements is installed. In order to minimize ground loop noise, it is often necessary to use a common ground system. The reader is referred to the works of Morrison (1978) and Ott (1977).

7.3.2 AMPLITUDE CHANGER AND OTHER COMPONENTS

Signal conditioning equipment generally implies a modification to the signal level. Occasionally, attenuators are used but usually signal amplification is required. Two of the important characteristics of an amplifier are its stability and its linearity. Of these, stability is the most important. Linearity of the amplifier should match the resolution of the digitizer.

Anti-aliasing filters are used to ensure that the signal is band limited before it is processed by the analog-to-digital converter. Their use is virtually universal and well understood. Two parameters of anti-aliasing filters are the sharpness of transition between passband and stopband, and the degree of phase tracking from one filter to another. The sharp cut-off feature allows reductions in sampling rates but risks the hazard that filter ringing may distort the signal near the stopband.

7.3.3 DIGITAL DATA PROCESSING

Analog-to-digital conversion units are available in many varieties. The primary consideration is the level of digitization commensurate with the type of data being measured. In general, digitization levels of 10 to 12 bits are adequate to provide resolution accuracies from one part in 256 to one part in 1024, respectively. The use of either of these rates allows a straightforward selection of other system components. If greater resolutions are desired and 14 bit or 16 bit digitizers are selected, the quality of signal conditioning equipment must meet more stringent requirements. To use the resolution provided by these higher digitization levels requires amplifiers of extremely high precision and linearity, which are considerably more expensive than those required for a 10 or 12 bit system. Selection of A-D converters is a nontrivial task: the reader is referred to Gordon (1978) and Analog Devices (1977).

Digitized data can be recorded on half-inch computer tape or on any of several disc recording media. Disc storage is emerging as the preferred approach because of its large capacity and its high data transfer rate. Discs offer a random access capability which is much more rapid than the sequential access inherent in tape systems. This feature is of primary importance in playback and handling of data. Tape units capable of handling the high transfer rate which can be achieved by most A-D converters are specialized units operating at high tape speeds. Their disadvantage is cost but the tape storage offers a virtually limitless repository. In general, sophisticated tape storage is not required.

A Fourier analyzer is almost essential for pulse-type testing, and they are recommended for this testing technique. Basically, the analyzer should be a two-channel device capable of analyzing a minimum of 1024 points with the option to "zoom" around a given point in the original 1024 points. Many other features and options are offered in transform processors of the type that are designed for incorporation into data acquisition systems. Most such units have internal computers to facilitate data processing, or the are interfaced intimately with other computers of standard design.

7.3.4 COMPUTER CONTROL

Finally, special mention is made of the desirability of centralized computer control of the data acquisition system and the general conduct of the testing. The use of minicomputers with their full input/output capabilities is an asset in handling data and in sequencing the test steps, either by prompting the operator or by controlling the final seconds prior to the test event. The availability of a computer permits manipulating data and the "quick look" analysis of data at the point where it is most important, immediately after a test event at the test site and before any of the transducers or test parameters have altered.

SECTION 8

PROCEDURES FOR SCHEDULING AND COST DETERMINATION

The tests discussed in this document are conceptually straightforward and yet the manner in which they will be implemented will require a concerted effort in order to integrate them within the framework of daily operations at functioning power plants. The intent of this section is twofold: (1) recommend a procedure to be implemented by the utility management to arrive at realistic and detailed estimates for labor requirements, equipment costs, computer time, schedules, milestones, and the conduct of a verification program; and (2) provide an approximate estimate of schedules and costs.

The second item is an attempt to arrive at realistic estimates. Some larger variations could be expected depending on the conditions and circumstances due to site uniqueness of a power plant. Moreover, these estimates include the total verification plans covered in Section 5. They are not limited to the test functions but include the analytical and support functions defined in the plans presented in Section 5.

8.1 SCHEDULING BY CPM TECHNIQUES

The procedure recommended for defining this planning work is via the critical path method (CPM) (Obrien, 1971). Those responsible for plant maintenance or facility add-on construction are already familiar with CPM or other network methods. The construction trades and crafts have been organized so that each individual activity involved in construction or maintenance has been assigned a standard time to accomplish the task. These unit times have been assembled into books that make it possible to estimate the time of completion and the dollar costs associated with conventional construction. The entire operation has reached a point of development so that it can be handled wholly within a planning office without input from the operating units. The situation for conducting tests on nuclear power plants represents the opposite situation since many of these tests have not heretofore been accomplished.

The purpose of this section is to provide some guidance for using the principles of CPM to achieve a more optimal program. Unlike the case for the trades mentioned above, test engineers, instrumentation personnel, designers, installation personnel, and the like must be queried in order to rationally determine work procedures, equipment usage, and costs for performing the many varied tasks that are attendant to large-scale testing. There is a high probability that their familiarity with CPM and networking techniques is limited. Yet their input is vital to a realistically planned program. This section serves to introduce this methodology for verifying a reactor facility.

The primary purpose of CPM scheduling is to provide a plan that will allow a reasonably constant level of effort to be allocated to the test program over its period of performance. To do so requires that individual tasks be broken down into small enough units so that they can be dealt with easily by the person responsible for that category of activity. It is crucial that each task be described as fully as possible by the operating personnel who will be responsible for it. One method for reducing the effort for each task is to describe the effort on a single sheet of paper or better, on a single filing card. The card should contain the task title, the detailed description of the task, and, most importantly, how it is planned to be accomplished. The card should also define the type and quantity of personnel required, any special or standard equipment which will be involved, and the time that personnel and equipment will be used. If this information cannot be placed on a single card, then the task is too large and it should be broken down into smaller units. Any particular task can be used as a starting point. After one task description has been completed, then the related tasks can be addressed by asking "What must be done immediately before this task?" and "What must be done immediately following this task?"

Once the cards for all the tasks have been completed, they are assembled into the total plan. This method reveals the interrelationships of the individual tasks and also allows rearranging of the sequence of tasks. The cards are then numbered in a manner prescribed by whatever networking technique is to be employed, a preliminary drawing of the network is made, and the entire project is transferred to computer input using standard CPM software. Having once committed it to the computer memory, the project manager can interrogate the program and optimize the overall project. The output from the computer program will be neatly plotted networks, tabulated lists of activities, determination of the critical path, the time to accomplish the various tasks, and summary costs of labor, materials, equipment, and related computer requirements.

8.2 PRELIMINARY COST AND SCHEDULE ESTIMATES

The procedures described above facilitate estimation of the costs of the test program. The program manager will use these data to budget the project.

Table 8-1 has been prepared to provide the plant manager with an approximate cost and schedule for implementing the high-explosive test program. The data in Table 8-1 are predicated on completing all phases delineated in Section 5.1 of this report. It must be kept in mind that these data are intended to be estimates for initial planning only. They do not replace the detailed planning that should be completed as described in Section 8.1 to reach a final estimate of cost and schedule.

The figures presented in Table 8-1 assume that two high-explosive tests will be performed in order to establish sufficient data to define the nonlinear response of the facility, including the primary structure and its equipments. The data are presented as a range of values. The upper range is an optimal plan that will enhance accuracy and reduce uncertainties to an expectedly acceptable level. The lower range is an estimate of a minimal program that assumes that the facilities basically respond linearly and that mathematical models will be simplified to linear or to linearized forms. It is probable that a realizable value is more nearly like the upper range.

No attempt has been made here to estimate the costs and schedules for performing pulser tests on major structures or on equipments and subsystems as these elements are site unique.

TABLE 8-1. PRELIMINARY COST AND SCHEDULE ESTIMATE IN PERFORMING HIGH-EXPLOSIVE TESTS IN ACCORDANCE WITH THE PROCEDURES DEFINED IN SECTION 5.1

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

SECTION 9

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APPENDIX

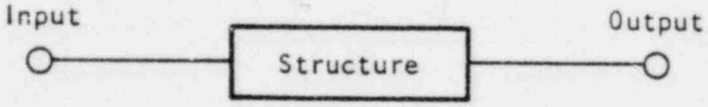
THEORETICAL DISCUSSIONS

APPENDIX

THEORETICAL DISCUSSIONS

A.1 SYSTEM FUNCTIONS

Dynamic properties of passive systems may be represented by Fourier transforms yielding a complex ratio of the input loading to the output response of the system. This complex ratio may be presented in the form of magnitude and phase, real and imaginary, and real versus imaginary, all as functions of frequency. Inverse transformation provides yet another form of this ratio in the time domain, the impulse function. The complex ratios obtained may be viewed as samples from a continuum both in space and bandwidth and are nonparametric. These functions can be determined analytically from a mathematical model or can be physically measured. Figure A-1 illustrates the concept:



- Impedance and inertance as function of frequency

$$Z(\omega) = \frac{\text{Input Force}}{\text{Output Velocity}} \quad \text{or} \quad \mathscr{A}(\omega) = \frac{\text{Output Acceleration}}{\text{Input Force}}$$

- Transfer function as function of frequency

$$\tau(\omega) = \frac{\text{Output Motion}}{\text{Input Motion}} \quad \text{or} \quad \frac{\text{Output Force}}{\text{Input Force}}$$

FIGURE A-1. SYSTEM FUNCTIONS

Mechanical inertance is an indicator of how a structure responds to a vibratory force. The response of a vibrated point on a structure is proportional to the inertance, which will be defined herein for a given frequency as the driving force on the structure divided into the acceleration of the same or another point on the structure. The motion of the structure may be recorded as displacement, velocity, or acceleration, and, when ratioed with input force, is defined by the following terms:

$\frac{\text{Force}}{\text{Displacement}}$ = Dynamic Stiffness

$\frac{\text{Displacement}}{\text{Force}}$ = Compliance

$\frac{\text{Force}}{\text{Velocity}}$ = Impedance

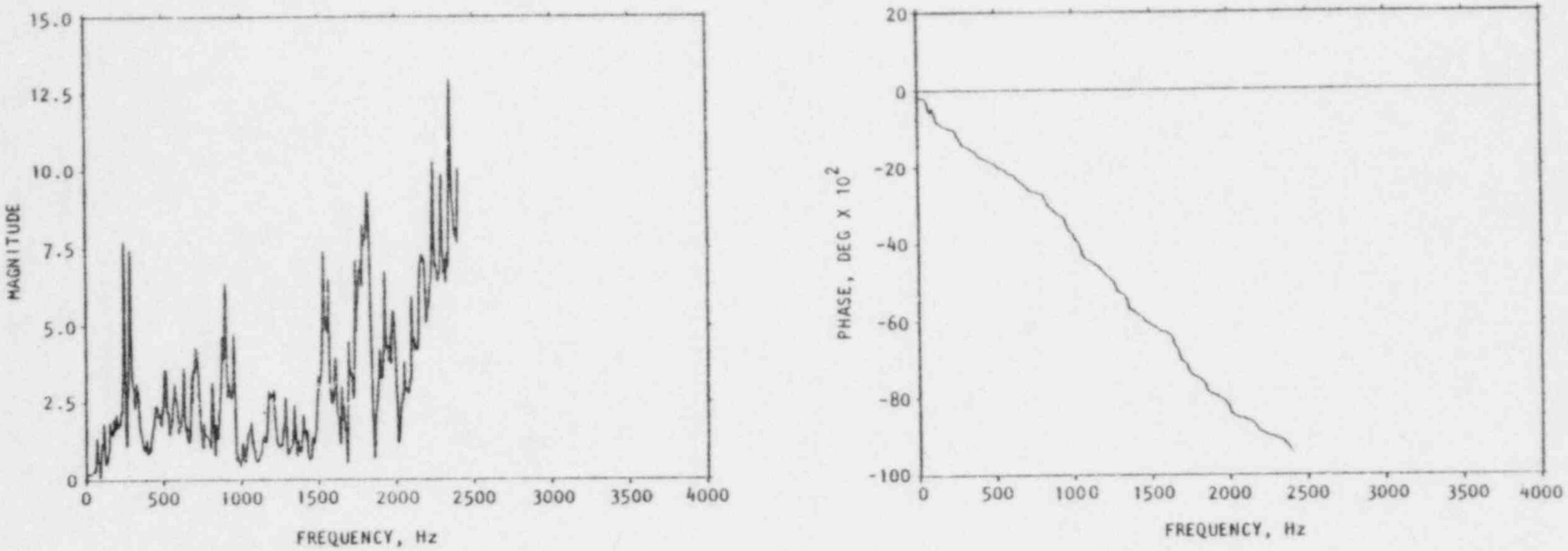
$\frac{\text{Velocity}}{\text{Force}}$ = Mobility

$\frac{\text{Force}}{\text{Acceleration}}$ = Dynamic Mass

$\frac{\text{Acceleration}}{\text{Force}}$ = Inertance

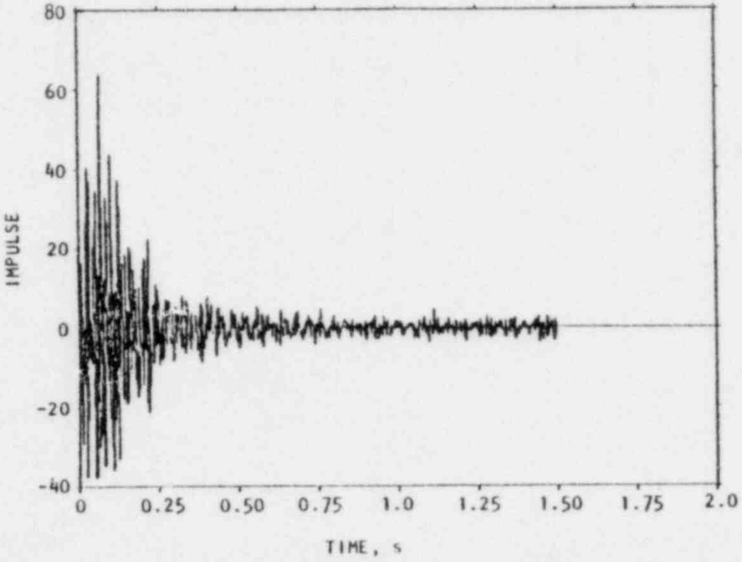
Another important function is the ratio of input motion to output motion or of input force to output force. This is defined as a transfer function. All of the above system functions may be inverse Fourier transformed into the time domain to obtain the impulse function. The impulse function is the response of a structure to an impulse represented by a Dirac delta function. A typical display of system function data is given in Figure A-2.

In many structures, motions orthogonal to the axis of input force of motion occur due to structural cross-coupling, as depicted in Figure A-3. Cross-axis coupling depends on the structure and may approach the magnitude of in-axis functions, as can be observed in Figure A-4. When this effect occurs, subsequent computations and analysis must account for this effect or substantial errors may result.



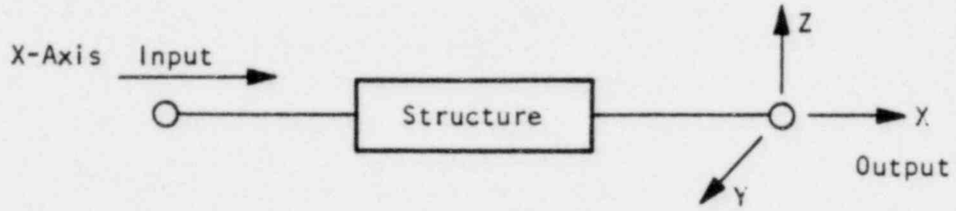
(a) Fourier magnitude: Inertance

(b) Fourier phase: Inertance



(c) Impulse: Inertance

FIGURE A-2. TYPICAL DIGITIZED SYSTEM FUNCTION OF A REINFORCED STEEL CONCRETE STRUCTURE



Cross-axes inertance as a function of frequency.

$$\mathscr{A}_{Y-X}^{(\omega)} = \frac{\text{Acceleration in Y-Axis}}{\text{Force in X-Axis}}$$

$$\mathscr{A}_{Z-X}^{(\omega)} = \frac{\text{Acceleration in Z-Axis}}{\text{Force in X-Axis}}$$

FIGURE A-3. CROSS-AXES SYSTEM FUNCTION

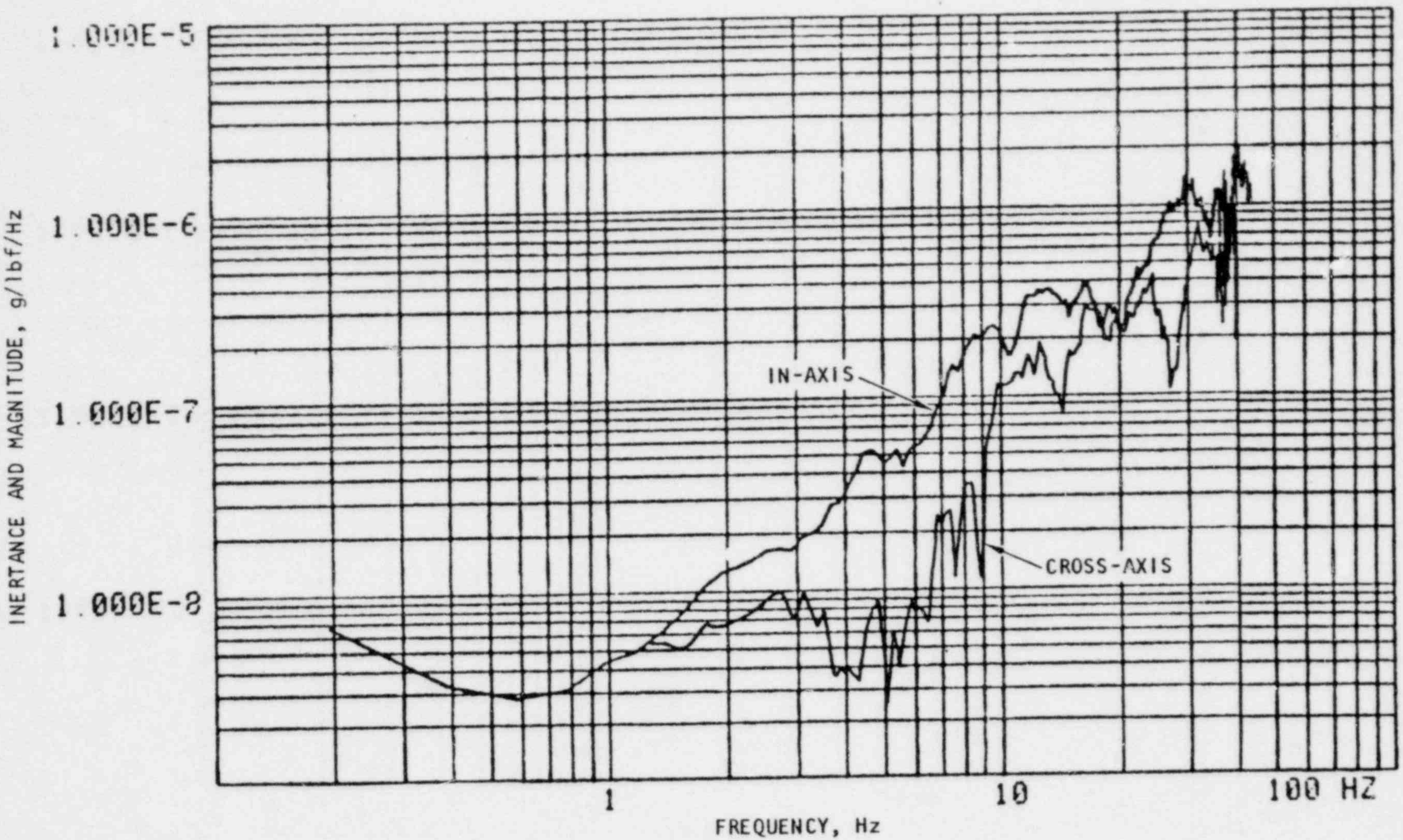


FIGURE A-4. OVERLAY OF CROSS-AXIS AND IN-AXIS AVERAGED INERTANCE FUNCTIONS FOR REINFORCED CONCRETE EARTHQUAKE-RESISTANT TWO-STORY BUILDING (460 FT LONG BY 160 FT WIDE)

A.1.1 Response

With both an input-loading function and an inertance or transfer function, responses may be determined (where the system is at least quasi-linear) by the relation in either the frequency or the time domains as:

$$r(t)\ (=)\ R(\omega) = \mathscr{A}(\omega)\ F(\omega) \tag{A-1}$$

or

$$r(t) = \int_{0}^{\tau} h(t - \tau)\ f(\tau)\ d\tau \tag{A-2}$$

where

$F(\omega)$ = Transform of the loading function $f(t)$

$R(\omega)$ = Frequency response of structure

$\mathscr{A}(\omega)$ = Inertance function

$h(t)$ = Impulse function of inertance $\mathscr{A}(\omega)$

$r(t)$ = Motion time response of structure

t = Time

τ = Time delay function for the convolution function

ω = Frequency

Response predictions made from multiple inertance functions and for multiple inputs of a structure are discussed in further detail in Section A.3.

A.1.2 Modes

Mode shapes, modal frequencies, and modal damping can be developed from system functions for a structure. Sufficient motion sensors on the structure are required to properly map each mode shape. In general, a series of independent damped sine waves is least-square fitted to the measured system function in either the time or complex frequency domain. This fitting process adjusts the amplitude, frequency, and damping constant for best fit for each resonance in the Laplace complex plane. The PARET program of Lawrence Livermore Laboratories is an example of this method. With each system function (every sensor location) fitted with a damped sine wave for each resonance, mode shapes, modal frequencies, and modal damping may be obtained. Modal information as extracted from measurements is used for comparison and improvement of computer models of the structure.

Historically, modal measurements were made on structures using rotating eccentric shakers for slow sine sweep and sine wave dwell. Some of the earliest studies were performed by Prof. Lydik Jacobsen, Stanford University, on campus buildings and on Hoover Dam in the early 1930's. Application of sine wave vibrators to complicated structures with closely spaced modes has proved to be difficult and has necessitated the use of multiple shakers (six or more in some cases) to adequately isolate modes. Modern techniques, which consist of broadband excitation, digital signal capture, and efficient computer algorithms are rapidly predominating and supplanting this older method.

A.1.3 Excitation

Methods of excitation for structures in the measurement of modal characteristics and system functions that have come into common use are:

- Slow sine sweep and dwell
- Random
- Rapid sine sweep (chirp)
- Impulse
- Pulse train

Selection of driving functions are constrained by physical hardware available to generate the required force levels, shaping characteristics, and bandwidth. The most commonly used force-function generators are electrodynamic and electrohydraulic shakers that produce continuous periodic (usually sinusoidal) functions that are controllable in amplitude, time duration, and frequency. With sophisticated control systems, these devices are also capable of generating random and complex force functions (chirp) as well as simple pulses. Higher capacity electrohydraulic shakers have capacities of up to 50,000 lbf.

Rotating eccentric mass shakers for slow sine wave and resonance dwell exist in several universities, government laboratories, and private corporations. Capacity of output forces vary up to 100,000 lbf.

Shock machines, impact hammers, pulse train generators, and explosives produce a second family of implosive or transient driving functions. These types of functions may include many pulses of varying forms (e.g., half-sine, triangle, square), depending on the required input. Important considerations with these devices are the generation of continuous functions in the frequency bandwidth of interest and adequate motion generation in the structure for favorable signal-to-noise ratios.

A.1.4 Noise

Practical use of impedance, inertance, and transfer functions has, until very recently, been severely limited due to the effects of noise. The mixing of signals and noise is given for an actual case in Figure A-5. Data measurements to obtain transfer and inertance functions are very susceptible to noise, in both acquisition and processing operations. These spurious effects are often of a magnitude sufficient to highly distort the measured signal.

Complex ratios of signals containing moderate amounts of noise exhibit a pattern similar to Figure A-6 for the inertance magnitude function $[\ddot{X}/F(j\omega)]$. Noise both enhances and reduces resonant peaks with no clear

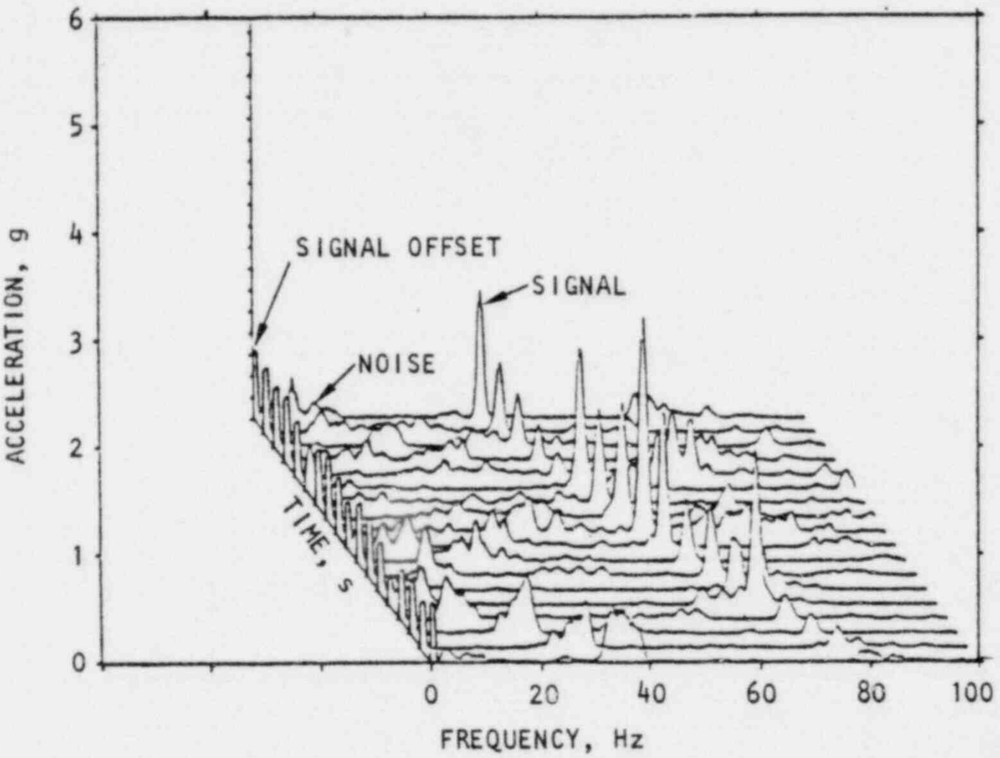


FIGURE A-5. DATA PROCESSING OF A DATA RECORD TO ILLUSTRATE MIXING OF SIGNALS AND NOISE

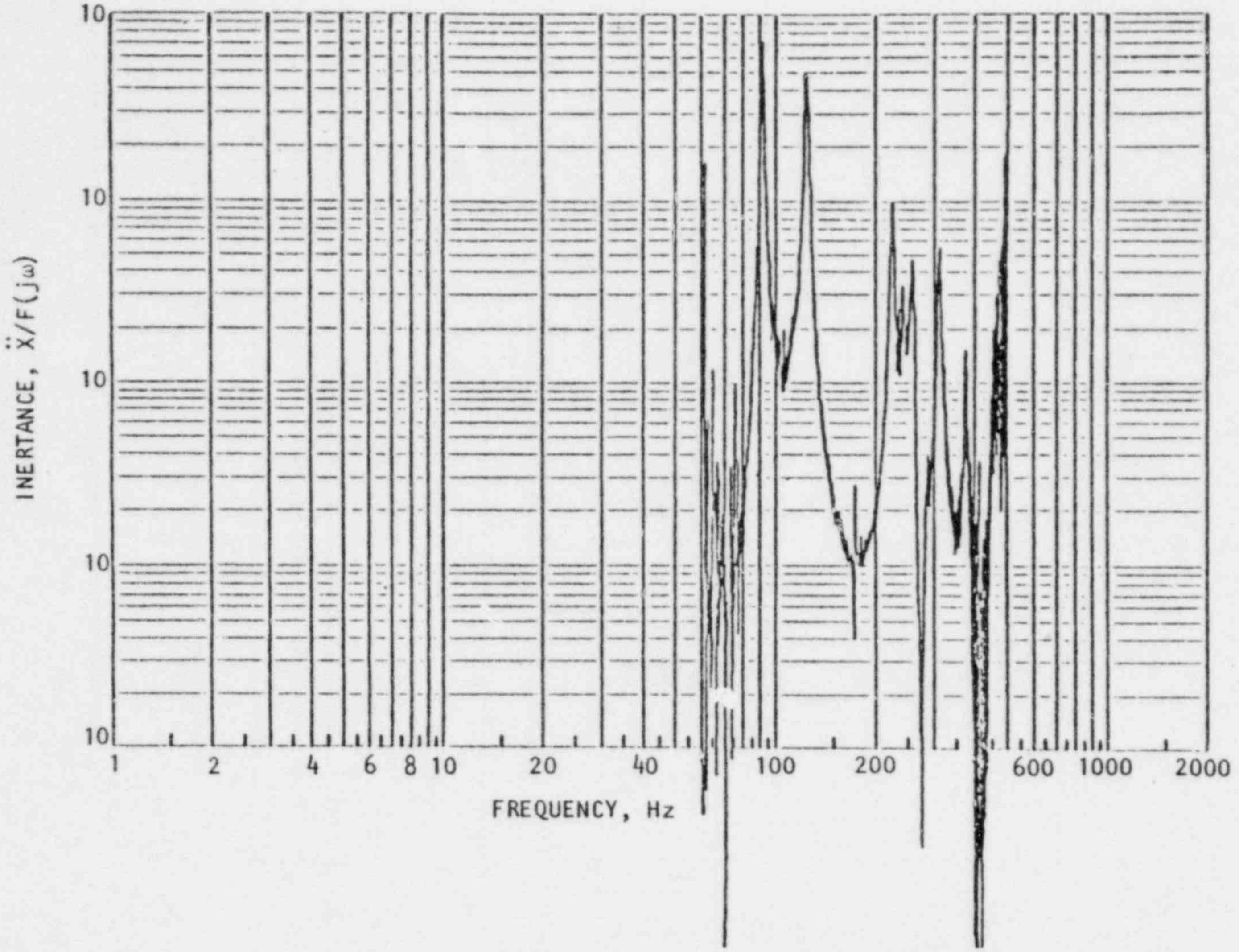


FIGURE A-6. EXAMPLE OF INERTANCE MAGNITUDE AFFECTED BY NOISE pattern. A more sensitive indication of noise can be found in the phase plot, $\phi(j\omega)$, of Figure A-7 when the phase is presented for 0 to $-n\pi$ deg rather than in the conventional form of ±180 deg. For noise-free, multiresonant linear systems, the phase plot should be essentially a monotonic line of phase as a function of frequency as in Figure A-2b. The slope of this curve provides the arrival time of the signal, which is given as:

$$\tau = \frac{\phi}{\omega} \qquad \text{(A-3)}$$

where

τ = Arrival time (sec)

ϕ = Phase change (radians)

ω = $2\pi f$ frequency (radians)

Examination of Figure A-7 shows an erratic pattern of phase, and this phase pattern can be observed in the plot of the impulse function of Figure A-8. The inertance impulse function of Figure A-2c is illustrative of a system function containing a reduced amount of noise.

Another method for the detection of noise is the coherence function that is expressed by the following:

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_x(f)\ G_y(f)} < 1 \qquad \text{(A-4)}$$

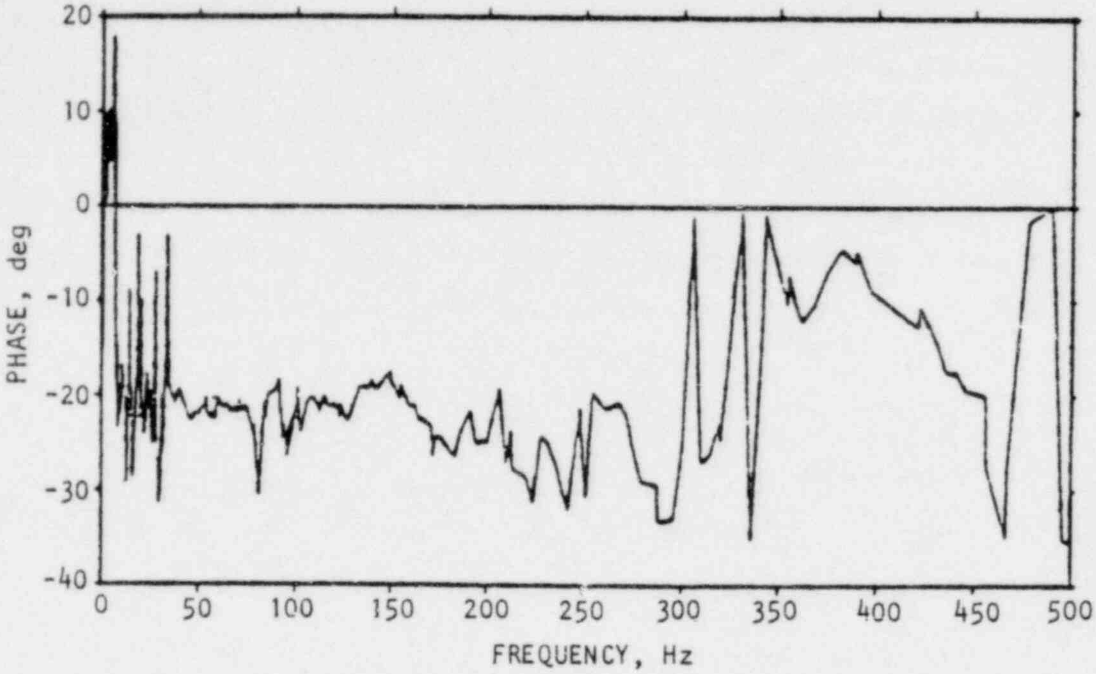


FIGURE A-7. PHASE MEASUREMENTS WITH HIGH NOISE CONTAMINATION

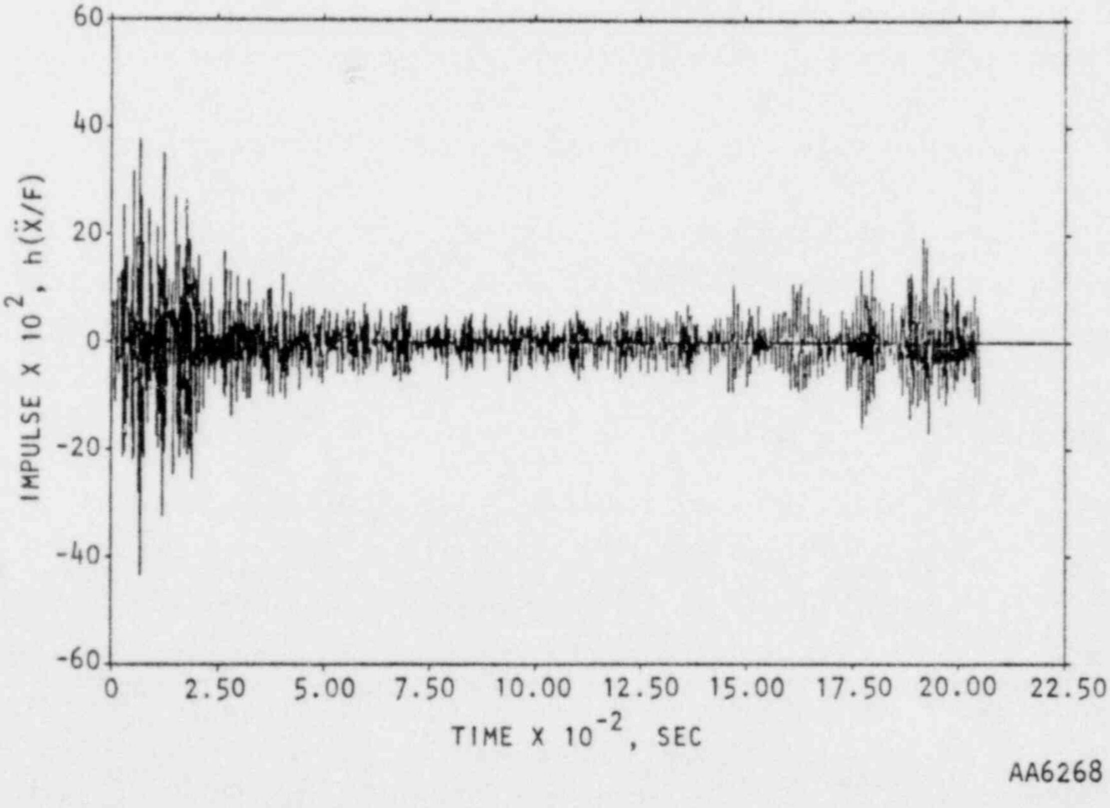


FIGURE A-8. INERTANCE IMPULSE FUNCTION OF A STRUCTURE WITH HIGH NOISE CONTAMINATION where

$G_x(f)$ = Power spectral density function, Fourier transform of autocorrelation function of $x(t)$ (input)

$G_{xy}(f)$ = Cross-spectral density function, Fourier transform of cross-correlation function of $x(t)$ and $y(t)$

$G_y(f)$ = Power spectral density function, Fourier transform of autocorrelation function of $y(t)$ (output)

$\gamma^2_{xy}(f)$ = Coherence function

When $\gamma^2_{xy}(f) = 0$ at a particular frequency, $x(t)$ and $y(t)$ are said to be incoherent (uncorrelated). When $\gamma^2_{xy}(f) = 1$ for all frequencies, then $x(t)$ and $y(t)$ are said to be fully coherent. If the coherence function is greater than zero but less than unity, one of three possible conditions exist:

1. Extraneous noise is present.
2. The system relating $x(t)$ and $y(t)$ is not linear.
3. $y(t)$ is an output due to an input $x(t)$ and other inputs.

Extraneous noise suppresses the coherence function, and the display of Figure A-9 serves as a detector for noise. The data in this figure indicates small noise contamination from 3.5 Hz to 25 Hz. Coherence is now a standard procedure and is used during measurements of structures to ascertain the quality of transfer and inertance functions. This coherence computation is accomplished using micro- and minicomputers that are commercially available for structural systems function measurements.

Noise occurs in measurements from numerous mechanical and electrical sources. The character of the noise may be periodic, quasi-periodic, and random. Periodic noise, as well as transducer drift and offset, is removed from the data by digital processing methods. Quasi-periodic and random noise is reduced by averaging the inertance and transfer function from repeated tests. The incoherence of noise and to a lesser extent quasi-periodic noise results in the time independence of these noise sources such that averaging

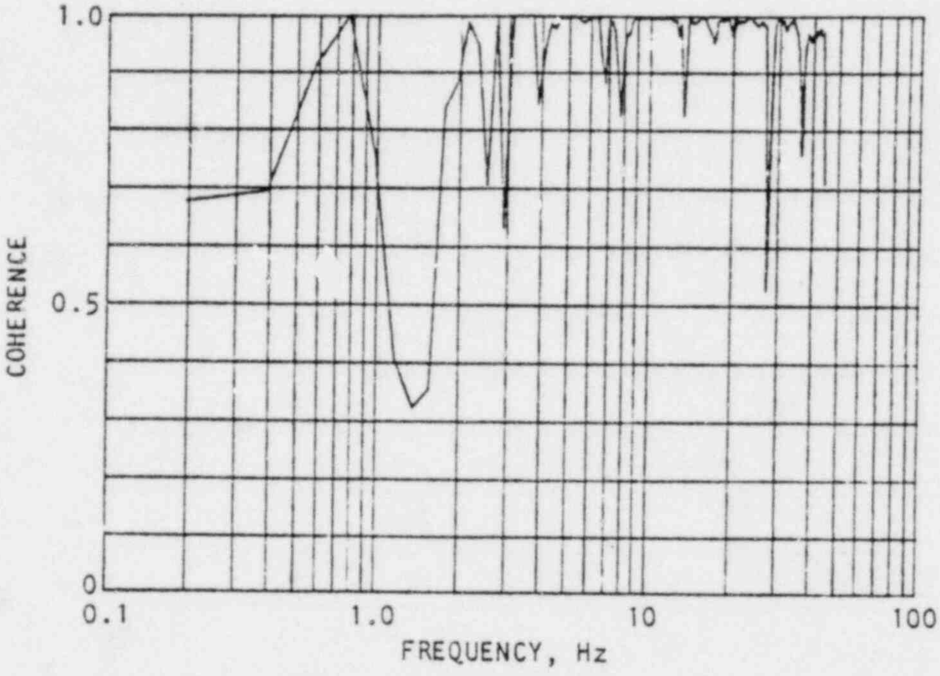


FIGURE A-9. COHERENCE FUNCTION OF AVERAGED INERTANCE MEASUREMENT ON A LARGE REINFORCED CONCRETE STRUCTURE of the system function reduces noise at the rate of the square root of the number of system functions averaged. This need for repeat tests has led to the recent adaptation of structural exciters that employ random vibration, rapid sine sweeps (chirp), impulse, and pulse trains to achieve more accurate system function measurements. A typical example of an averaged inertance function is shown in Figure A-10; this same function with no averages is shown in Figure A-6. The advent of mini- and microcomputers for use during system function tests store data for each test in memory and upon command compute averages of the transfer or inertance (system) functions.

Several other methods are also used for noise reduction. These methods include multipoint smoothing and polynomial fit. The functions shown in Figure A-2 employed an iterative phase-averaging method that was constrained to conserve signal energy and to lower the average of noise effects (Safford et al., 1975). Waveform parameterization by Prony's method as used by Lawrence Livermore Laboratory's PARET procedure is also effectively used for noise reduction (Poggio, 1978). In the PARET procedure, successive sets of curves are fitted to an impulse function with each set initiated at different time offsets. The extracted parameters of the curves are subsequently averaged. These methods are used on postprocessing test data and can be applied to both single records or functions already averaged during tests to obtain additional noise reduction.

A.1.5 Sensitivity of System Function Measurements

The sensitivity that can be easily attained with these new data processing systems (minimum noise) is presented in Figures A-11 and A-12. Figure A-11 illustrates measurements taken on a flush buried reinforced concrete structure with the exciter force and accelerometer at the same location (drive point inertance). Inertance function measurements with and without a spring isolator were made. These functions are overlay plotted in Figure A-12a with the difference between the curves or the effective spring

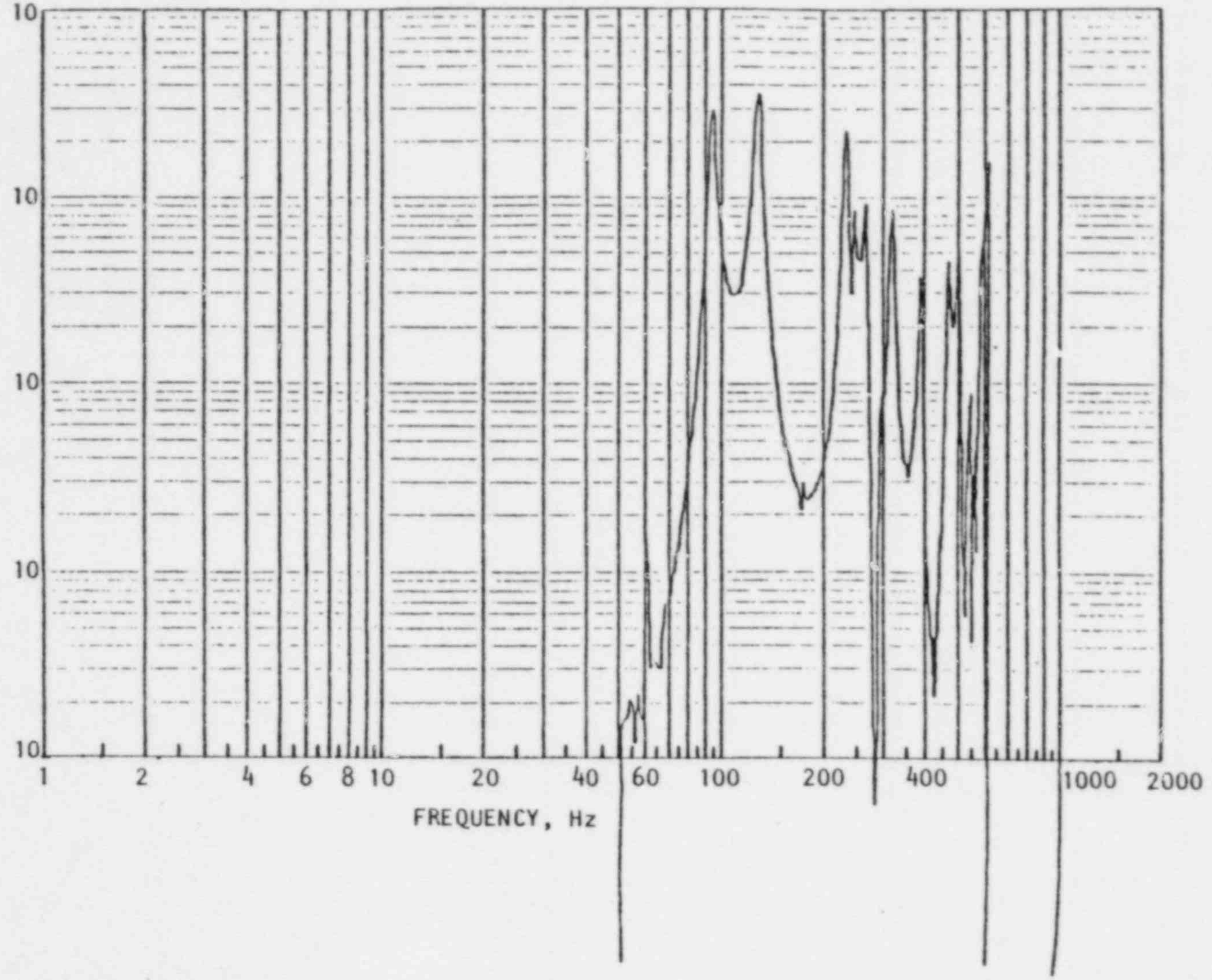
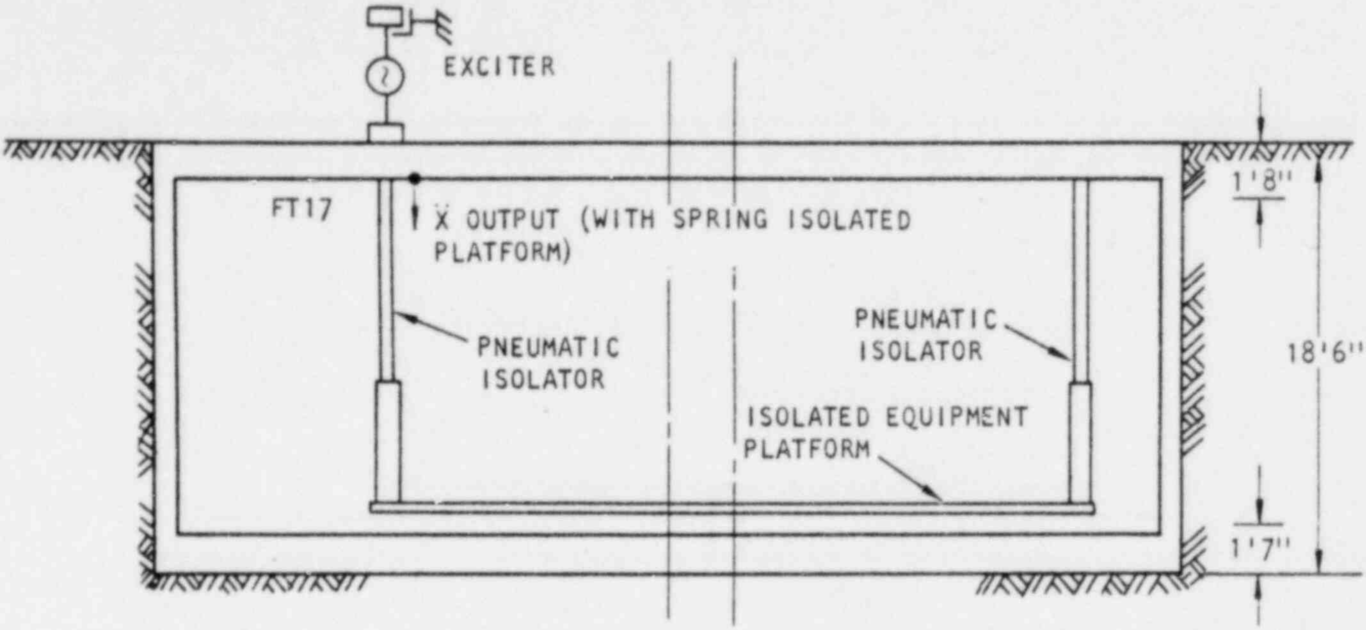
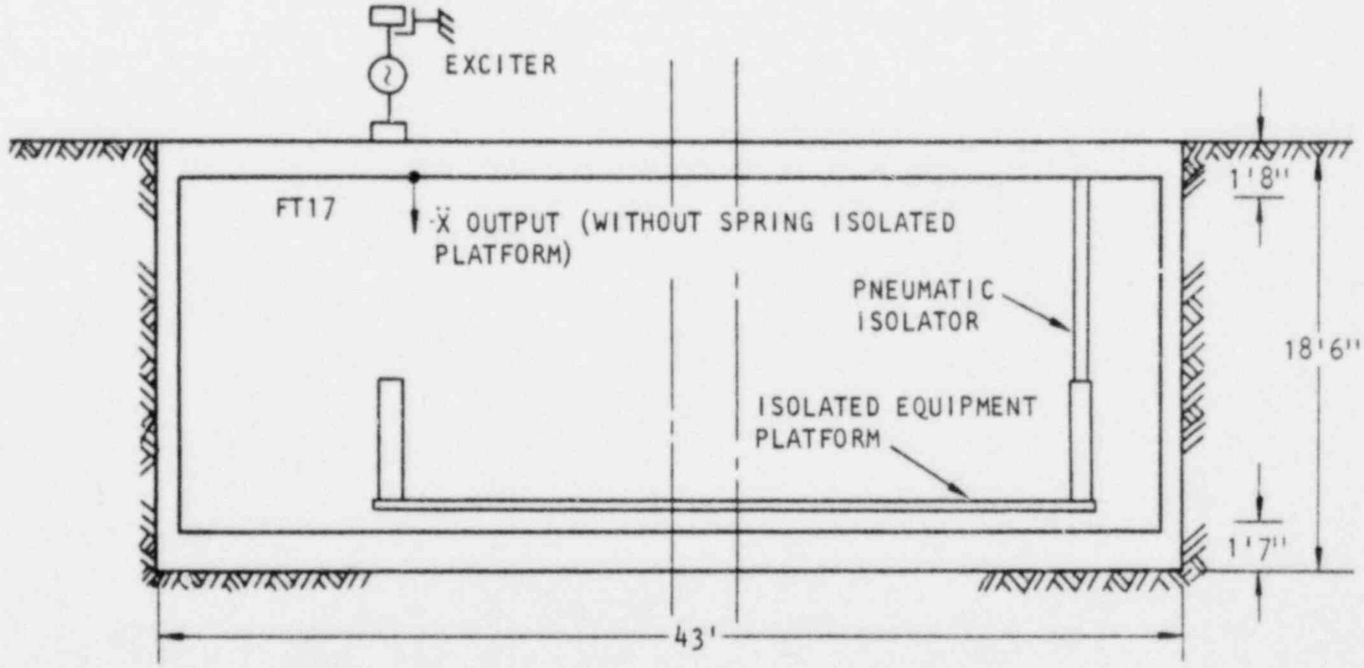


FIGURE A-10. INERTANCE MAGNITUDE AVERAGE FUNCTIONS TO REDUCE RANDOM NOISE (See Fig. 6-9)

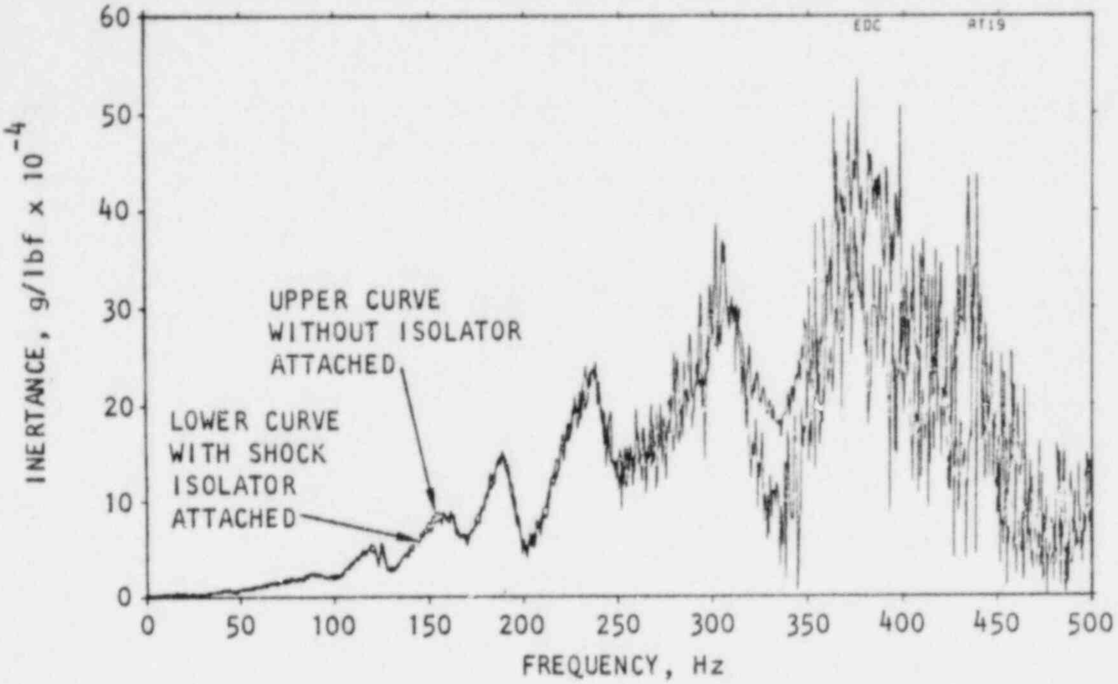


(a) Driving Point inertance measurement with spring isolated equipment platform connected to roof

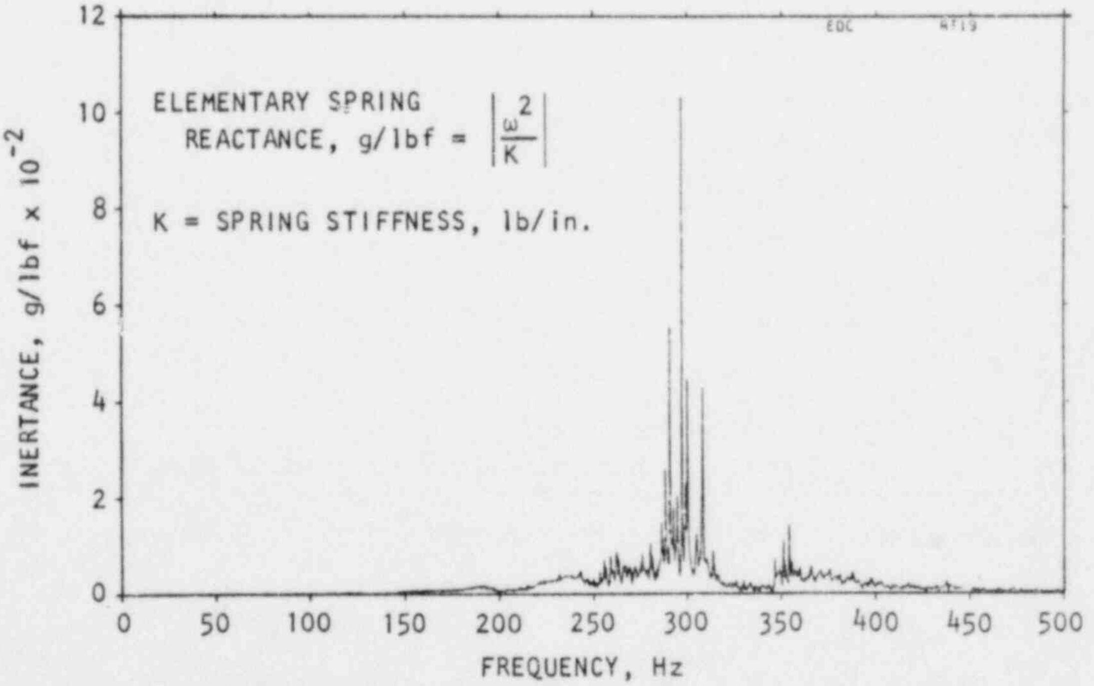


(b) Driving point inertance measurement without spring isolated equipment platform connected to roof

FIGURE A-11. ELECTRICAL DISTRIBUTION CENTER DRIVE POINT INERTANCE MEASUREMENT WITH AND WITHOUT SHOCK-ISOLATED PLATFORM ATTACHED



(a) Driving point inertance of 20-inch thick roof with and without a shock isolator attached



(b) Effective spring reactance extracted from inertance function of Fig. 6-15(a)

FIGURE A-12. SENSITIVITY OF LOW NOISE INERTANCE MEASUREMENTS IN DETECTING VERY LARGE IMPEDANCE MISMATCH OF STRUCTURAL ELEMENTS reactance shown in Figure A-12b. Extraction of the spring isolator reactance is performed in the complex frequency domain as follows:

$$\frac{1}{\mathcal{A}_L} = \frac{1}{\mathcal{A}_F} + \frac{1}{\mathcal{A}_E} \tag{A-5}$$

$$\mathcal{A}_E = \frac{\mathcal{A}_F \mathcal{A}_L}{\mathcal{A}_F - \mathcal{A}_L} \tag{A-6}$$

where

$\mathcal{A}_E$ = Drive point inertance of isolator

$\mathcal{A}_F$ = Drive point inertance of facility

$\mathcal{A}_L$ = Drive point inertance of facility and isolator

The significance of Figure A-12 occurs in the ability to measure and differentiate between the stiff 20-in. thick reinforced concrete roof and the very low stiffness of the pneumatic isolator. This result could only be obtained with low-noise measurements. Below 150 Hz in Figure A-12b, the isolator is spring-like; but above this frequency, complex reaction of isolator hardware is evident (isolator pendant and pneumatic piston).

A.1.6 Motion Reduction in Structures by Dynamic Interaction of Internally Mounted Equipment and Machinery

The foregoing information covering the sensitivity of inertance measurements presages the influence of massive equipments in attenuating building motions induced by earthquakes. Facility motions may be altered to a considerable extent by the dynamic reaction of internally mounted equipment. The degree of motion alteration may be determined by the relative driving point inertances of the facility and of the equipment at the attachment locations. Prediction of facility motions without inclusion of equipment dynamic interaction with the structure can lead to considerable error. These errors can be reduced or eliminated by the techniques presented in this section. Other important applications of these techniques are to be found where equipment is changed, added to, or removed from a facility.

The effect of this equipment and machinery interaction in power plant structures may yield significant motion reduction over current earthquake motion predictions, particularly those motion predictions based on somewhat elementary finite element models.

The effect of equipment on a facility is to alter its unloaded motions. This alteration may be expressed at points of connection as follows, and the concept is illustrated in Figure A-13:

$$\underset{\text{load}}{\ddot{X}(t)} \quad (=) \quad \underset{\text{load}}{\ddot{X}(j\omega)} = \underset{\text{no load}}{\ddot{X}(j\omega)} \left[\frac{\mathcal{A}_E}{\mathcal{A}_E + \mathcal{A}_F}\right] \tag{A-7}$$

where

$\underset{\text{load}}{\ddot{X}(t)}$ = Acceleration-time history of equipment and facility

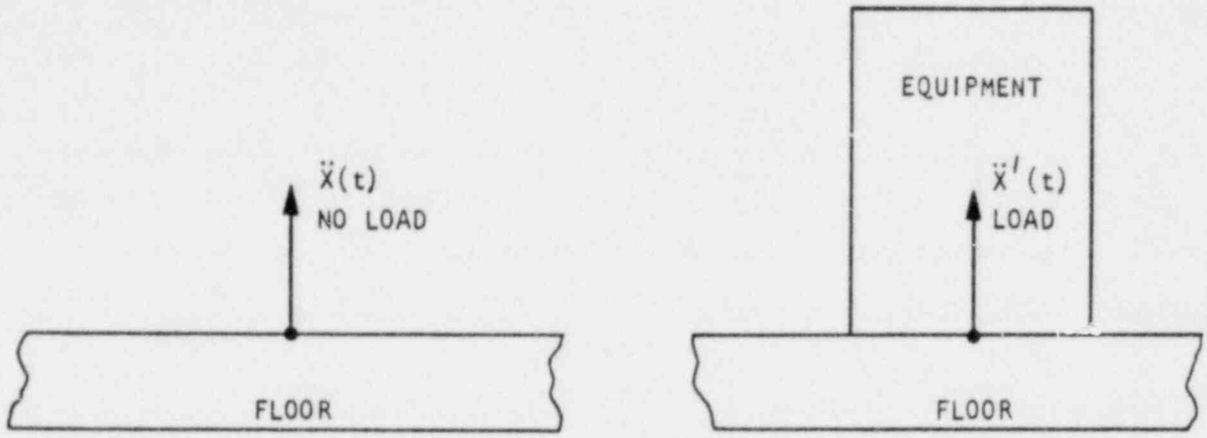
$\underset{\text{load}}{\ddot{X}(j\omega)}$ = Acceleration-frequency spectrum of equipment and facility

$\ddot{X}(j\omega)$ = Acceleration-frequency spectrum of facility only (no equipment)

$\mathcal{A}_F$ = Driving point inertance of facility

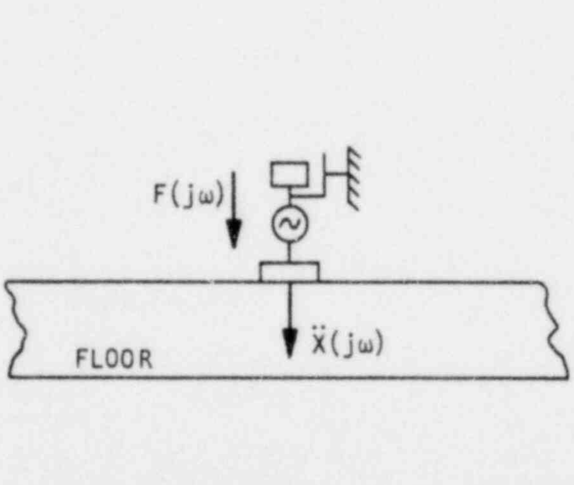
$\mathcal{A}_E$ = Driving point inertance of equipment

Practical verification of the above effects were uncovered by inertance measurements of a 1/12-scale model structure and its prototype (Safford et al., 1978). The 1/12-scale model structure duplicated the basic prototype in walls, floor columns, including scaled rebar, but not internally mounted equipment. The prototype was a five-story structure 125 ft high, 194 ft wide, and 210 ft long, with 3-ft thick exterior walls.



(a) Earthquake vibration of unloaded floor

(b) Earthquake vibration of floor and equipment



(c) Measurement of driving point inertance $\left[\ddot{X}(j\omega)/F(j\omega)\right]$ of facility

(d) Measurement of driving point inertance $\left[\ddot{X}(j\omega)/F(j\omega)\right]$ of equipment

FIGURE A-13. MOTION REDUCTION OF FACILITY FLOOR BY THE ADDITION OF EQUIPMENT

Identical inertance measurements were made on both model and prototype structures with a force exciter on the roof and accelerometers on the 5th, 4th, 3rd, and 2nd floors. The prototype structure was fully equipped with internally mounted machinery and equipment. While meticulous efforts were made to achieve 1/12 geometric scaling, the inertance measurements disclosed substantial differences, particularly for the 2nd and 3rd floors of the prototype where large amounts of equipment were mounted. The effect of this equipment was to reduce the predicted time-history motion responses of the 3rd floor by 70% and of the 2nd floor by 34%. The 4th and 5th floors, lightly loaded with equipment, were in geometric scale within experimental variability. These results are presented in Tables A-1 and A-2. Section A.4 presents further information dealing with response motion predictions and tests on these model and prototype structures.

A.2 PULSE OPTIMIZATION PROGRAM

Transient shock tests on massive equipment, systems, and buildings to simulate the motions induced by an earthquake are limited by current test techniques. Simulating multiaxis loading on large structures with many degrees of freedom represents a difficult problem, as it is impractical to generate continuously varying forces of sufficient magnitude. On the other hand, short duration forces of large magnitudes over a wide frequency range can be generated and controlled by pulse generators (Safford and Masri, 1974). Most importantly, these pulse generators may be placed on the structure at locations of convenience without regard to the input location of an earthquake, as can be seen in Figures A-14 and A-15.

Since a discrete number of pulses superficially presents an appearance quite different from a continuous earthquake excitation signal, it becomes necessary to select the pulses in such a way that the resulting vibration of the structure matches as closely as possible the response (e.g., displacement, velocity, or acceleration) produced by the continuous force, as determined by an appropriate error criterion. This approach (Masri et al., 1975) is shown in Figure A-15.

TABLE A-1. SCALING FACTORS, MODEL TO PROTOTYPE, FOR GEOMETRIC AND INERTANCE MEASUREMENT SCALING

	Scale Factors				Difference (Reference Geometric)	
	Inertance		Geometric			
Floor	Displacement Factor, a	Frequency Factor, b	Displacement Factor, λ	Frequency Factor, λ	Displacement, %	Frequency, %
5th	18.4	10.2	12	12	+ 53	-15
4th	10.5	12.7	12	12	- 12	+ 6
3rd	25.3	14.0	12	12	+111	+17
2nd	34.5	9.7	12	12	+188	-19

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TABLE A-2. ACCELERATION RESPONSE SCALING, MODEL TO PROTOTYPE, GEOMETRIC AND INERTANCE MEASUREMENT SCALE FACTORS

	Acceleration Response Scaling				Difference (Reference Geometric)	
	Inertance		Geometric			
Floor	Fourier Magnitude, λ^3/ab^2	Time History & Shock Spectra, λ^3/ab^2	Fourier Magnitude	Time History & Shock Spectra, $1/\lambda$	Fourier Magnitude, %	Time History & Shock Spectra, %
5th	$\frac{1}{1.11}$	$\frac{1}{11.3}$	1	$\frac{1}{12}$	+10	-6
4th	$\frac{1}{0.98}$	$\frac{1}{12.4}$	1	$\frac{1}{12}$	-2	+3.3
3rd	$\frac{1}{2.87}$	$\frac{1}{40}$	1	$\frac{1}{12}$	+65	+70
2nd	$\frac{1}{1.88}$	$\frac{1}{18.2}$	1	$\frac{1}{12}$	+47	+34

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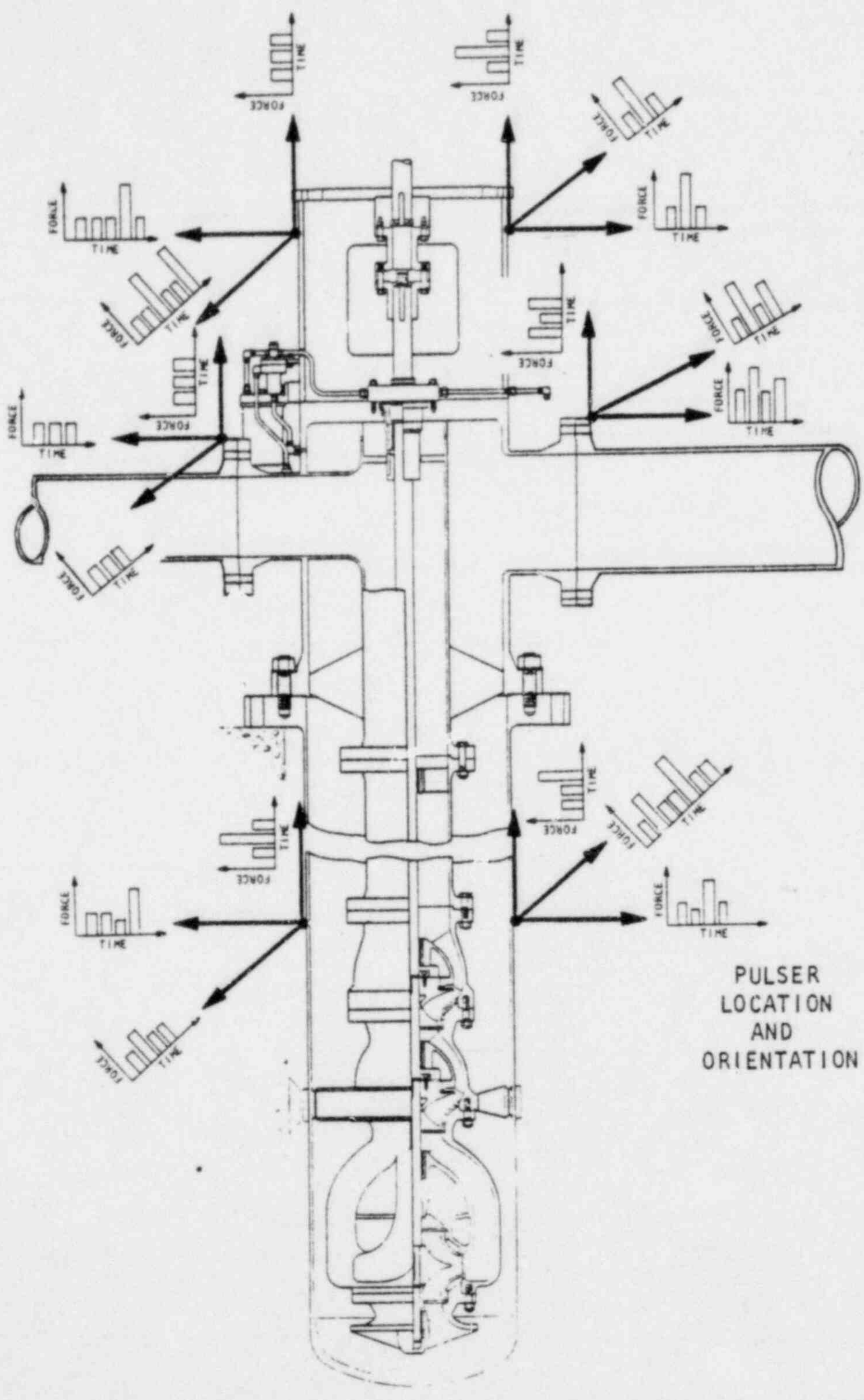
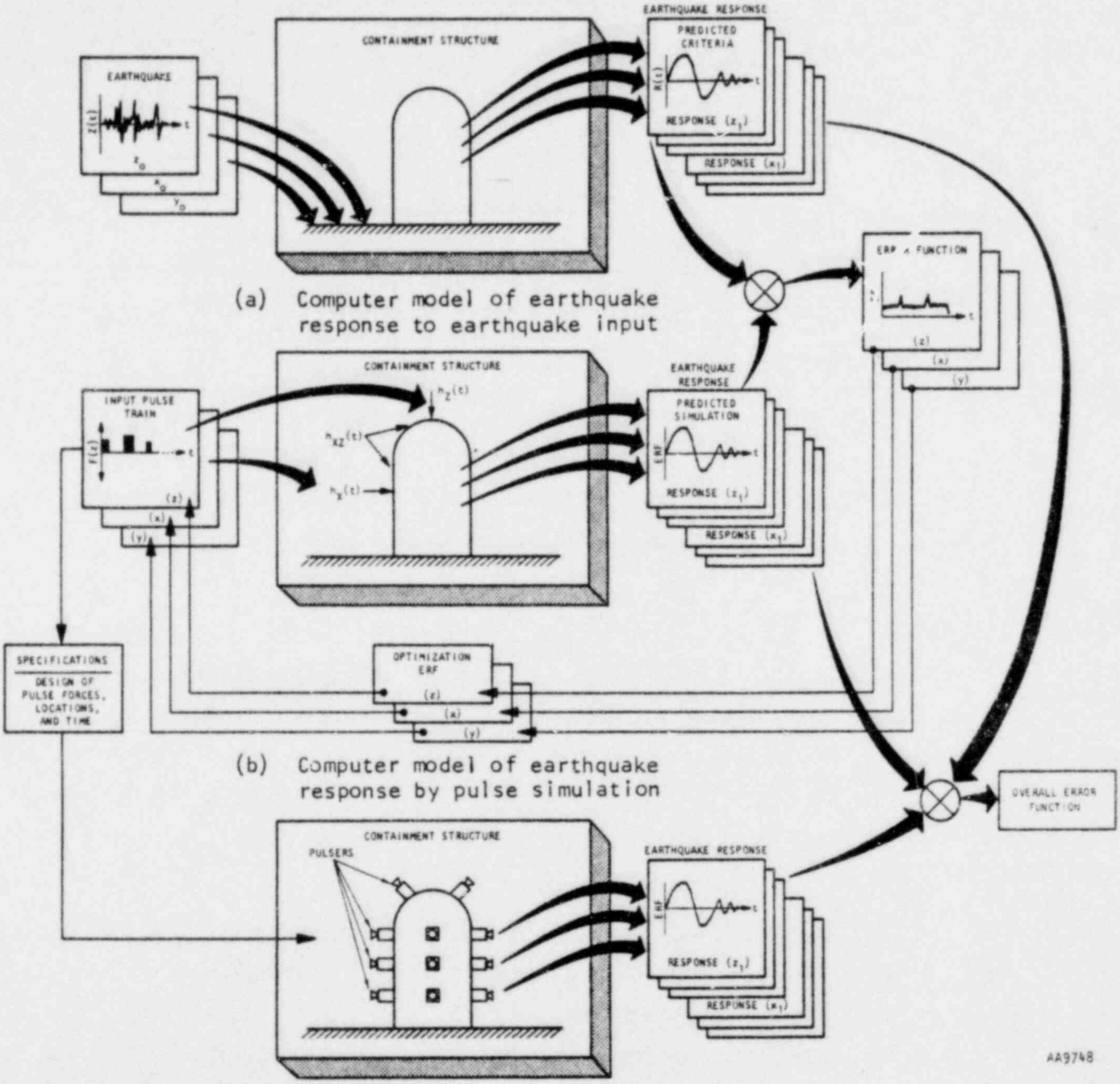


FIGURE A-14. MULTI-AXES PULSE SIMULATION OF PRIMARY COOLANT PUMP TO MATCH EARTHQUAKE TIME-HISTORY MOTION



(a) Computer model of earthquake response to earthquake input

(b) Computer model of earthquake response by pulse simulation

(c) Pulse test to simulate earthquake response

FIGURE A-15. PROCEDURE FOR PULSE TEST OF NUCLEAR REACTOR CONTAINMENT STRUCTURE TO SIMULATE EARTHQUAKE RESPONSE

It is important to note that the method of Figure A-15 requires that the criterion response to the continuous input be known, which would generally not be true in practice. To accomplish this objective, the approach here requires that (1) a mathematical model of the system under study is known and (2) the inputs of interest (e.g., earthquake) are given. Under these conditions the "criterion response" can be calculated and used to obtain the pulse train for the simulated test.

In general, the response-time history of a structure under simulated test should show a reasonable approximation to the expected environmental phenomena for meaningful hardness/vulnerability evaluation.

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

When pulse tests are performed, errors in the match between criteria and simulated response may be uncovered due to inaccurate or limited mathematical modeling of the system. In the linear region of structure response, these errors may be minimized by use of measured transfer functions to correct the computer model earthquake response predictions and the pulse-simulated response.

Inertance measurements or analytic functions between the vertical and horizontal input loading points on the building or equipment are first made or created. The measurements include vertical, horizontal, and cross-axis directions. Converted to impulse functions, they are used in the development of the pulse train. Analytic functions or measurements are in the form of inertance--the complex ratio of output acceleration to input force $\left[\frac{\ddot{X}}{F}(jw)\right]$.

Pulse trains are a series of rectangular forces that vary in amplitude, time duration, and initiation time. An iterative optimization algorithm is used to tailor pulse trains by convolution with the inertance impulse-function measurements or analytic functions to cause the building to have response accelerations matching motions experienced in an earthquake. A highly efficient search algorithm is used, which employs an adaptive random search technique (Masri et al., 1976). Given a multi-axes test for a linear response motion bandwidth of 0 Hz to 35 Hz, pulse trains are generated in accordance with the following matrix:

$$
\begin{array}{lccccccc}
\text{Lateral Direction} & \ddot{X}_{H1} & & h_{H1} & h_{H1/H\perp 1} & h_{H1/V1} & & F_{H1}\\
 & \vdots & & \ddots & & & & \vdots\\
 & \ddot{X}_{Hn} & & h_{Hn} & & \cdot & & F_{Hn}\\
\hdashline
\text{Longitudinal Direction} & \ddot{X}_{H\perp 1} & & & h_{H\perp} & \cdot & & F_{H\perp 1}\\
 & \vdots & = & & \ddots & & & \vdots\\
 & \ddot{X}_{H\perp n} & & & h_{H\perp} & \cdot & & F_{H\perp n}\\
\hdashline
\text{Vertical Direction} & \ddot{X}_{V1} & & & & h_{V1} & \cdot & F_{V1}\\
 & \vdots & & & & \ddots & & \vdots\\
 & \ddot{X}_{Vn} & & & & & h_{Vn} & F_{Vn}\\
 & \text{Output Acceleration} & & \multicolumn{4}{c}{\text{Structural Impulse Function Matrix}} & \text{Input Pulse Generators}
\end{array}
\qquad (A\text{-}8)
$$

Influence of the off-diagonal terms, which represent interaction and coupling effects, will vary for each structure. Evaluation of these terms is required to minimize the size of the matrix by discarding those with minimal influence.

Optimization iterations are continued until error functions, as given below for both vertical and horizontal motions of the structure to be tested, are equal to or less than a specified error. Error functions are normally set at 5%.

$$\text{erf} = \frac{\int_0^t \left(\ddot{X}_{\text{Ref.}} - \ddot{X}_{\text{Pulsed}}\right)^2 dt}{\int_0^t \ddot{X}^2_{\text{Ref.}}\, dt} \qquad \text{(A-9)}$$

An adaptive random search method is used to determine the pulse trains for both the horizontal and vertical axes. These pulses are convolved with the impulse function matrix shown above to induce motions in the structure. Since each individual pulse in the train is characterized by the independent parameters of amplitude, duration, and initiation time, a total of three parameters is needed to define each pulse and each direction.

The algorithm for the adaptive random search consists of alternating sequences of a global random search with a fixed value for the step size variance followed by searches for the locally optimal variance (σ). Figure A-16 illustrates the adaptive algorithm whereby a very wide-range search selects the best standard deviation of step size (σ) for the coarseness of the increments used, followed by a sequential precision search of finer increments. As the rate of convergence decreases, a new precision search is made, but is directed towards a smaller step size. At selected iteration intervals, the wide-range search is reintroduced to prevent convergence to local minima.

The specification developed for the pulse train as developed from the procedures in Figure A-15 is used to program the pulse generating devices.

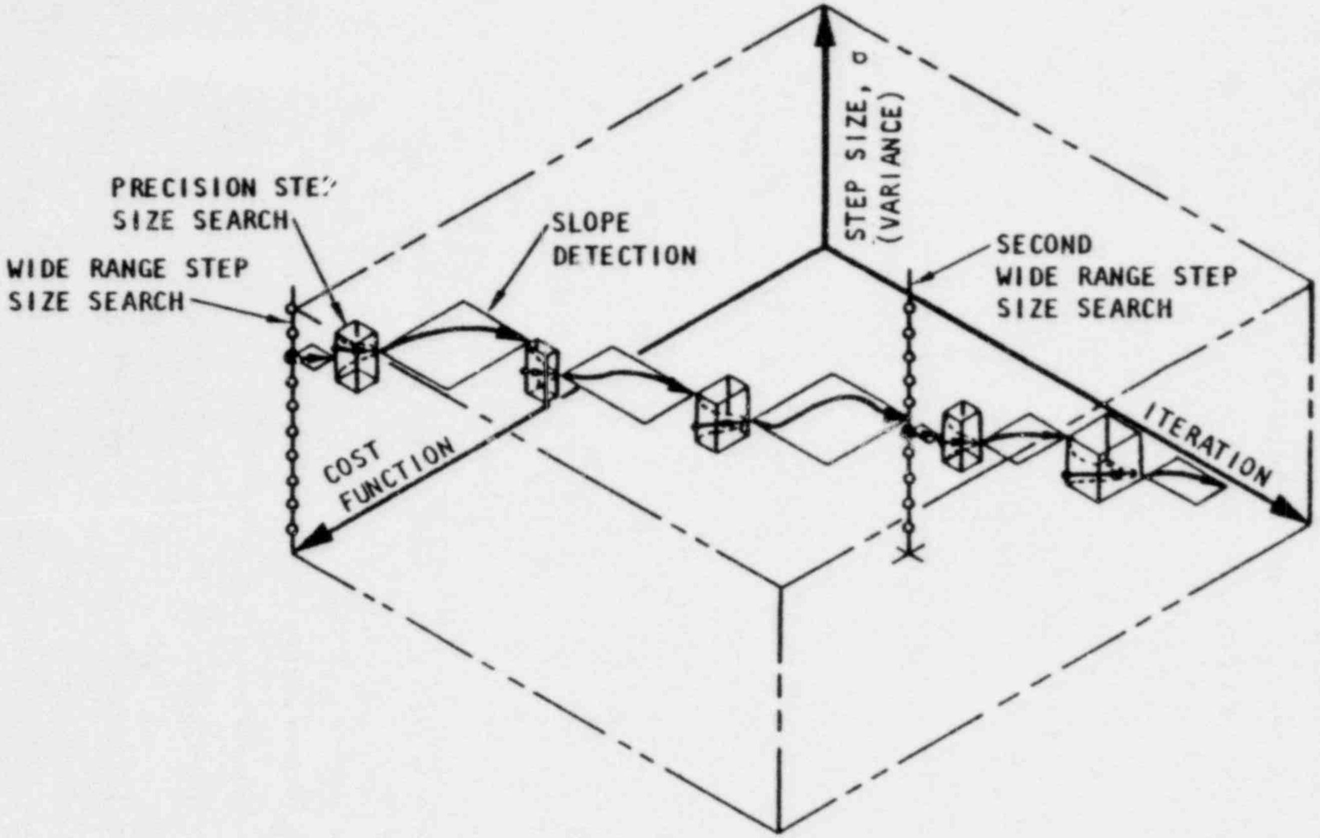


FIGURE A-16. ADAPTIVE STEP SIZE SEARCH, BOTH WIDE RANGE AND PRECISION, FOR RAPID CONVERGENCE OF COST FUNCTION

A.3 SYSTEM IDENTIFICATION

System identification is applied to structures for which partial or no information is known of its parameters or characteristics. Knowledge or measurements of dynamic inputs and responses may be utilized in a systematic manner to extract full or partial specification of the structures' parameters and characteristics. Extraction procedures for information embedded in the input-output data is broadly covered by system identication procedures. Useful information concerning this subject is available in the references by Bekey (1969) and Eykhoff (1974).

System identification procedures may be organized into (1) parametric and nonparametric methods, (2) search regions, and (3) search techniques. This classification is given in Figure A-17 and covers the major methods.

A considerable amount of knowledge is available for most of the structures and critical systems of a power plant. This information includes design configurations and material properties and is sufficient to develop computer models for earthquake prediction responses, which has been the procedure to date. The computer models may be configured into forms identical to the measured input and output tests used in systems identification for comparison, evaluation, and verification. Information extracted from systems identifications tests and from computer models provides means of improving earthquake prediction responses of power plants by a more precise specification of:

- The linear parameters (mass, stiffness, damping, mode shapes, and modal frequencies)
- The characteristics of mathematical model and actual (measured) characteristics (transfer functions, impedance function, impulse function, restoring function)
- The order of the mathematical model and order of the actual (measured) system
- The nature of linearity or nonlinearity present

PARAMETRIC

- LEAST SQUARES ESTIMATION
- MARKOV ESTIMATION
- MAXIMUM LIKELIHOOD ESTIMATION
- MINIMUM VARIANCE (BAYES) ESTIMATION
- KALMAN

NONPARAMETRIC

- IMPULSE RESPONSES
- TRANSFER FUNCTIONS
- COVARIANCE FUNCTIONS
- SPECTRAL DENSITIES
- VOLTERRA SERIES
- WIENER SERIES
- RESTORING FUNCTIONS

SEARCH REGIONS

- PARAMETER SPACE
- FUNCTION SPACE

SEARCH TECHNIQUES

MINIMIZATION PROCEDURES USING DERIVATIVES

- ▲ GRADIENT METHODS (METHOD OF STEEPEST DESCENT)
- ▲ SECOND-DERIVATIVE METHODS (NEWTON'S METHOD)
- ▲ CONJUGATE GRADIENT METHODS (PARTAN METHOD)
- ▲ VARIABLE METRIC METHODS (FLETCHER-POWELL)

MINIMIZATION PROCEDURES WITHOUT USING DERIVATIVES

- ▲ DIRECT SEARCH (RELAXATION)
- ▲ POWELL'S METHOD
- ▲ RANDOM SEARCH METHODS

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FIGURE A-17. CLASSIFICATION OF IDENTIFICATION METHODS

A.3.1 Parametric Methods

Modal analysis approximates structures by an orthogonal and independent (no cross coupling) set of equations. Errors are introduced by using this approach if nonproportional damping is present (Tang, 1960); if the damping is low, these errors are minimal ($\geq 2\%$ equivalent viscous damping).

Various types of excitation of structures can be used for the purpose of identification. The measured data is subsequently processed such that curve fitting in the form of the following equations, for example, can be accomplished

$$f(t) = \sum_{n=1}^{N} B_h e^{\alpha_n t} \cos\omega_n t \qquad \text{(A-10)}$$

where B_n is the initial amplitude, ω_n is the frequency of vibration, and α_n is a damping constant. This curve fitting may be accomplished either in the time domain or the frequency domain. Each independent curve properly fitted (in a least square sense) represents a mode of vibration. Application of this procedure to all measured points of the structure results in the mode shape, modal frequency, and modal damping (Poggio et al., 1978).

The problem of resolving differences between computer model modes and measured modes can be handled by estimation theory. Minimum variance (Bayes) is best suited as this approach considers both the structural model and the test data to be random. A probability distribution function must be specified or developed for the data and for the structural parameters. With a search region in parameter space, a variety of search techniques (Fig. A-17) are available to minimize error and to determine optimal values of parameters and measurements. Satisfactory convergence for the class of methods under consideration requires that the structure be linear or "piecewise linear" and that the order of the model and the actual structure be compatible. The step-by-step procedure of the foregoing is presented in Figure A-18 and the overall process of parametric system identification is depicted in Figure A-19.

BLOCK 1

READ:

- NUMBER OF MEASURED NATURAL FREQUENCIES
- NATURAL FREQUENCY MODE NUMBERS
- MEASURED NATURAL FREQUENCIES

BLOCK 2

READ:

- NUMBER OF MEASURED MODE SHAPES
- NUMBER OF MODAL DISPLACEMENTS MEASURED IN EACH MODE
- SYSTEM DISPLACEMENTS THAT CORRESPOND TO MEASURED MODAL DISPLACEMENTS
- MEASURED VALUE OF MODAL DISPLACEMENTS

BLOCK 3

READ:

- NUMBER OF SYSTEM DEGREES OF FREEDOM
- NUMBER OF SUBSTRUCTURES
- NUMBER OF SUBSTRUCTURES WITH PARAMETERS TO BE IDENTIFIED
- NUMBER OF DEGREES OF FREEDOM IN EACH SUBSTRUCTURE
- NUMBER OF ATTACHMENT DEGREES OF FREEDOM IN EACH SUBSTRUCTURE
- MASS, STIFFNESS, AND COMPATIBILITY MATRICES FOR ALL SUBSTRUCTURES WITH KNOWN PROPERTIES

CALCULATE:

- CONTRIBUTION TO SYSTEM MASS AND STIFFNESS MATRICES FROM ALL SUBSTRUCTURES WITH KNOWN PROPERTIES

BLOCK 4

READ:

- MASS, PRIOR STIFFNESS AND COMPATIBILITY MATRICES FOR ALL SUBSTRUCTURES WITH UNKNOWN PARAMETERS

CALCULATE:

- MASS AND PRIOR STIFFNESS MATRICES FOR ALL SUBSTRUCTURES WITH UNKNOWN PARAMETERS IN TERMS OF SYSTEM COORDINATES

BLOCK 5

CALCULATE:

- SYSTEM MASS AND STIFFNESS MATRICES

BLOCK 6

CALCULATE:

- ANALYTICAL NATURAL FREQUENCIES AND MODE SHAPES

BLOCK 7

CALCULATE:

- DIFFERENCE BETWEEN MEASURED AND ANALYTICAL NATURAL FREQUENCIES AND MODAL DISPLACEMENTS

BLOCK 8

READ:

- ACCEPTABLE NATURAL FREQUENCY AND MODAL DISPLACEMENT DIFFERENCES

BLOCK 9

CALCULATE:

- ACCEPTABLE NATURAL FREQUENCY AND MODAL DISPLACEMENT

BLOCK 10

READ:

- NUMBER AND LOCATION OF CRITICAL MODAL DISPLACEMENTS
- PERCENTAGE ON NONCRITICAL MODAL DISPLACEMENTS IN EACH MODE THAT MUST BE ACCEPTABLE

BLOCK 11

CALCULATE:

- ACCEPTABILITY OF ANALYTICAL MODEL

BLOCK 12

READ:

- PARAMETER ITERATION OPTION
- EXPERIMENTAL ERROR MATRIX
- STRUCTURAL PARAMETER ERROR MATRIX

BLOCK 13

CALCULATE:

- MEASUREMENT/STRUCTURAL PARAMETER SENSITIVITY MATRIX

BLOCK 14

CALCULATE:

- REVISED VALUES OF STRUCTURAL PARAMETERS

GO BACK TO

BLOCK 5 AND REPEAT BLOCKS 5 TO 14
(BLOCKS 8, 10 AND 12 ARE NOT REPEATED)

FIGURE A-18. BLOCK DIAGRAM FOR MINIMUM VARIANCE (BAYES) ESTIMATION FOR STRUCTURAL MODES

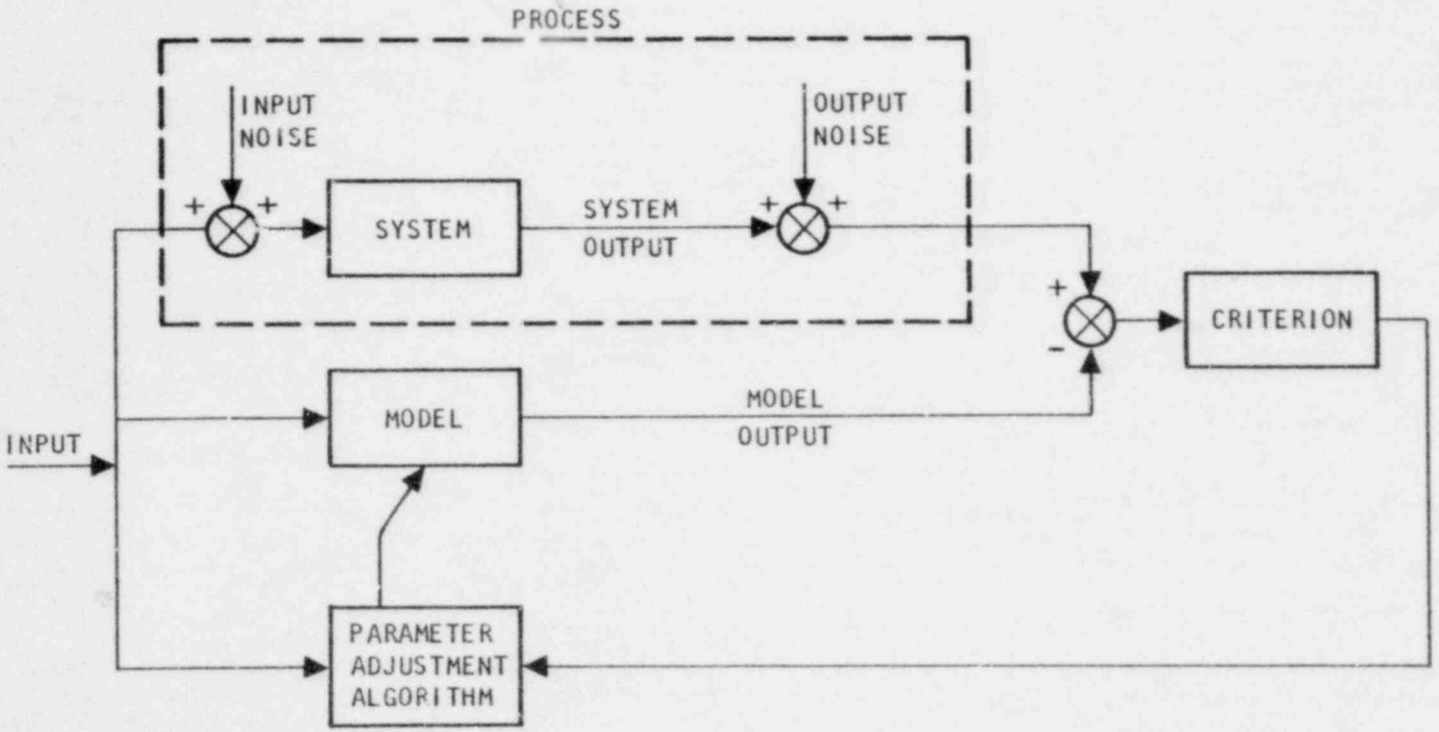


FIGURE A-19. BLOCK DIAGRAM FOR PARAMETRIC SYSTEM IDENTIFICATION

A.3.2 Nonparametric Methods

A basic characteristic of these methods is that no a priori assumptions are made regarding the structural configuration of the system to be identified. Instead, the identification problem is reduced to a search in "function space." Various search techniques may be used consistent with the complexity of systems to be identified. The block diagram depicting this problem is shown in Figure A-20.

Nonparametric methods may be applied to both linear and nonlinear systems. For the case of linear systems, impulse and transfer functions, while appearing to be largely deterministic, have a noise contamination problem (random, periodic, and quasi-periodic) that often requires estimation methods. Nonlinear system identification can be characterized by the use of Volterra series or by Wiener Kernels using orthogonal Laguerre functions. Use of these functions and their limitations are covered in Masri and Caughey (1979).

Nonlinear "restoring function" identification is most appropriate for power plants. This "restoring function" is applied in areas of gross nonlinearity of power plants such as soil-structure interaction, impact of internal parts and equipment, and snubbing action on piping. This method was discussed in Section 5 of the main text for HE tests of power plants where the power plant and soil are treated as a hysteretic system.

For an arbitrary excitation location to an output location, a chain can be evolved in which the masses of the system are defined (a requirement for this procedure) as given in Figure A-21.

The computational procedure applies estimates of the restoring function iteratively in the form of Chebyshev two-dimensional orthogonal polynomials until convergence is obtained. A wide range of nonlinearities may be handled by this method, including discontinuities. Both computer execution time and storage requirements are minimal.

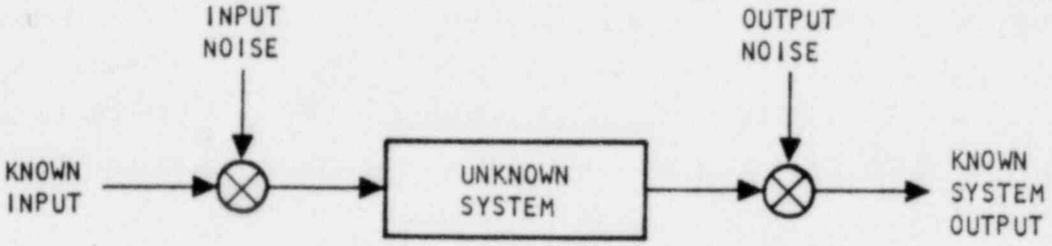


FIGURE A-20. BLOCK DIAGRAM FOR NONPARAMETRIC SYSTEM IDENTIFICATION

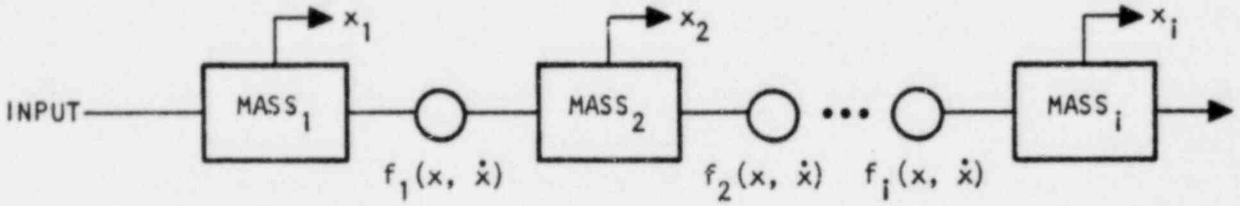


FIGURE A-21. CHAIN MODEL FOR "RESTORING FORCE" EXCITATION

An illustrative example is presented in Figures A-22 through A-25 of a Van der Pol oscillator. The Van der Pol oscillator has a restoring force

$$f(x, \dot{x}) = -\varepsilon(1 - x^2)\, \dot{x} + x \tag{A-11}$$

which involves cross-coupling between x and $\dot{x}$. Figures A-22 and A-23 show the identification data generated by subjecting the Van der Pol oscillator to swept sine excitation. Figure A-22c gives the results of the identification procedure and compares the actual and the estimated restoring force. Figures A-24 and A-25 show three-dimensional plots of the measured and estimated restoring force surface under swept sine excitation.

A more direct application of this method site/structure interaction is for the case of a hysteretic oscillator. This application is significant as the restoring force is not expressible in polynomial form. Figure A-26 gives the state variable plot for the hysteretic oscillator, and Figures A-27 and A-28 show the three-dimensional display of the results.

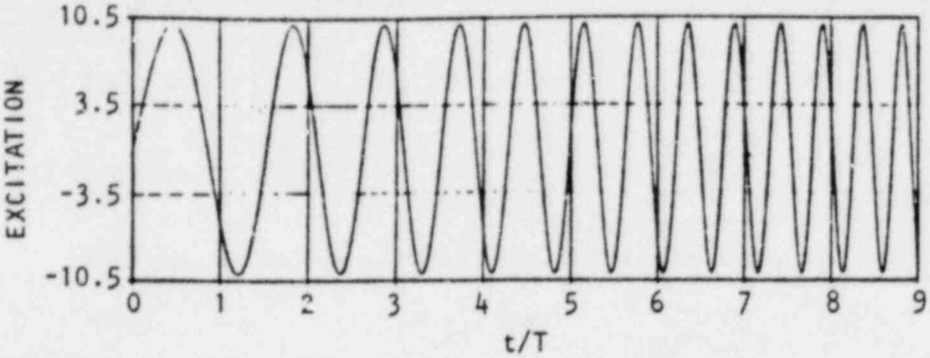
Forms of excitation other than swept sine (such as pulse trains and random) may be used for this process. This "restoring force" method is given in more detail in reference Masri and Caughey (1979).

A.4 MOTION RESPONSE CALCULATIONS FROM INERTANCE MEASUREMENTS OF A NUCLEAR POWER PLANT

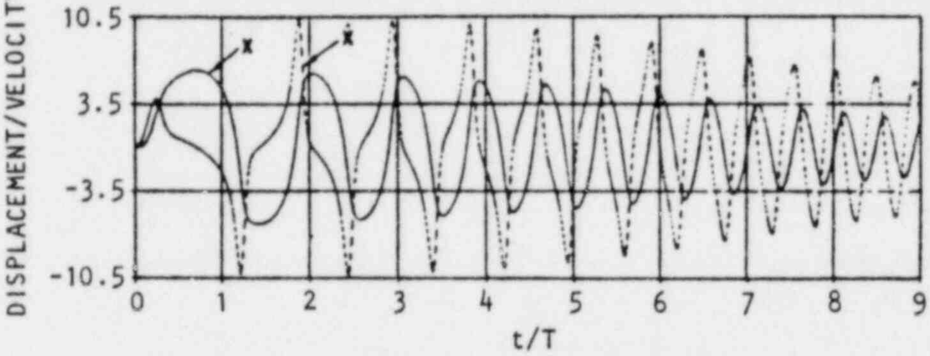
The most accurate motion response calculation can be made for complicated structures in the linear range by convolving external input excitation with the measured structural system functions (inertance). This procedure is applicable to major structures as a replacement for or comparison with conventional finite element calculations. Two conditions contribute to this prediction accuracy:

a. System function (inertance) measurements are made on the power plant in the as-built condition with equipment installed. The

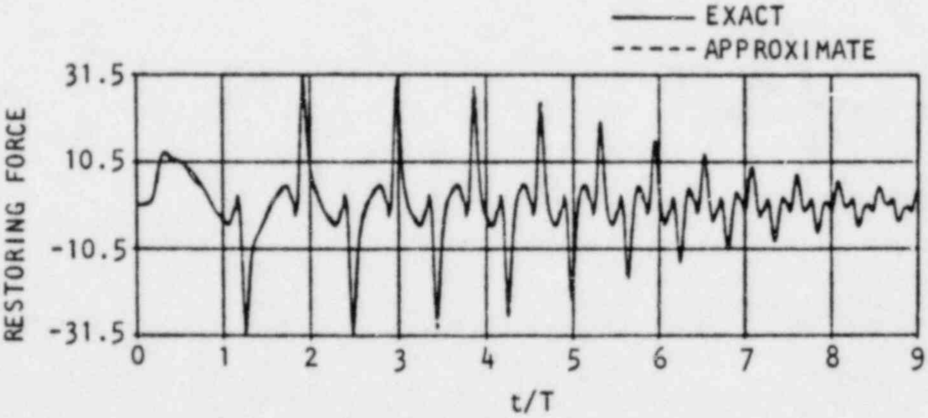
$$F(t) = \sin \Omega(t)t \quad \frac{\Omega(0)}{\omega} = 0.5 \quad \frac{\Omega(T_s)}{\omega} = 1.5 \quad \frac{T_s}{T} = 10 \quad \frac{\Delta t}{T} = 0.01$$



(a) Excitation

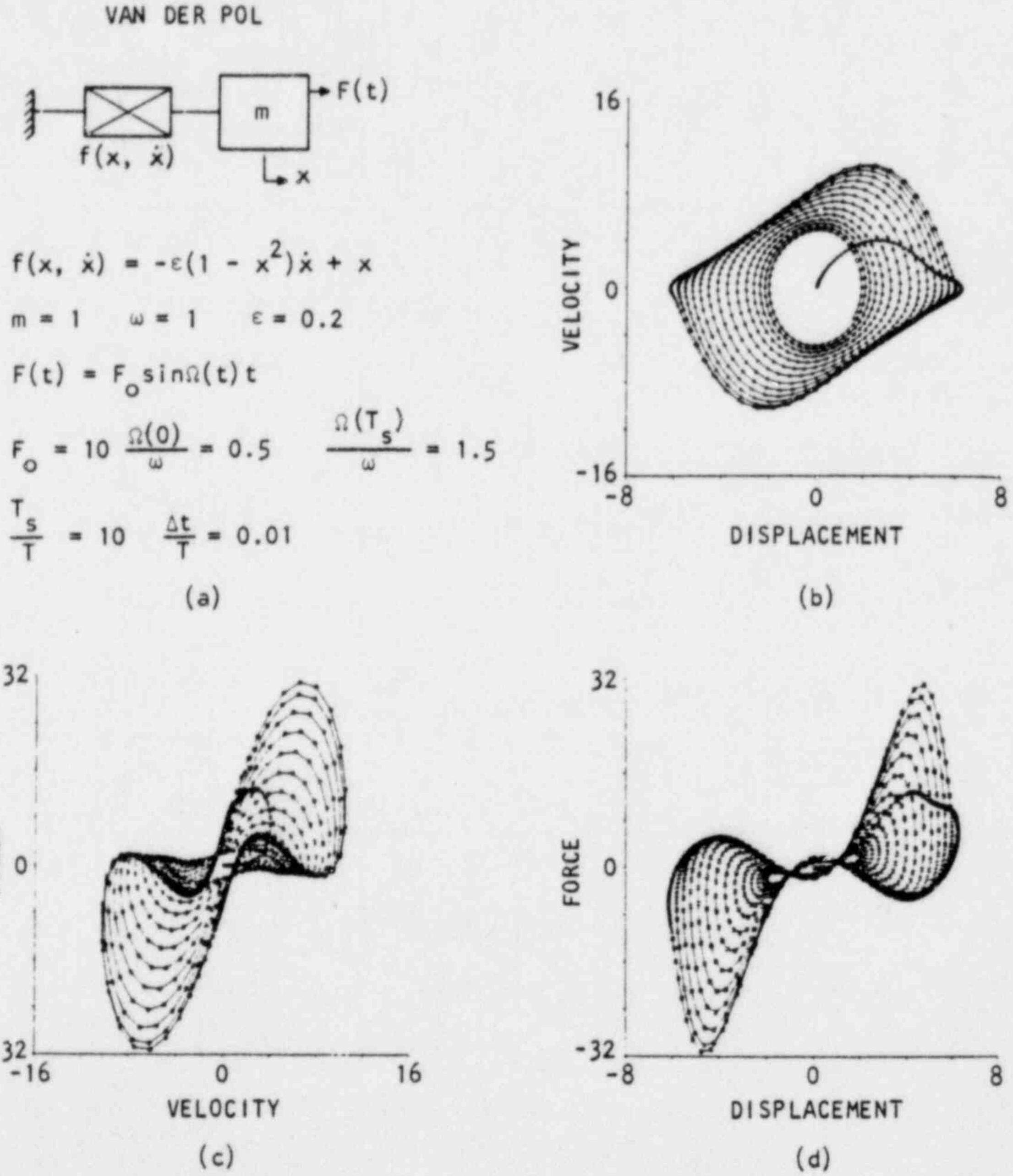


(b) Displacement/velocity



(c) Measured and estimated restoring force

FIGURE A-22. IDENTIFICATION DATA FOR THE VAN DER POL OSCILLATOR UNDER SWEPT-SINE EXCITATION



$f(x, \dot{x}) = -\varepsilon(1 - x^2)\dot{x} + x$

$m = 1 \quad \omega = 1 \quad \varepsilon = 0.2$

$F(t) = F_o \sin\Omega(t)t$

$F_o = 10 \quad \frac{\Omega(0)}{\omega} = 0.5 \quad \frac{\Omega(T_s)}{\omega} = 1.5$

$\frac{T_s}{T} = 10 \quad \frac{\Delta t}{T} = 0.01$

(a) (b)

(c) (d)

FIGURE A-23. STATE-VARIABLE PLOT FOR THE VAN DER POL OSCILLATOR UNDER SWEPT-SINE EXCITATION

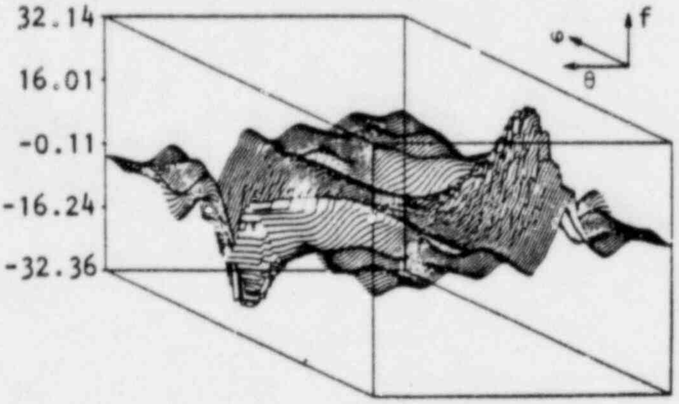


FIGURE A-24. INTERPOLATED VALUES OF $f(x, \dot{x})$ AT EQUIDISTANT POINTS IN θ AND Φ FOR THE VAN DER POL OSCILLATOR UNDER SWEPT-SINE EXCITATION

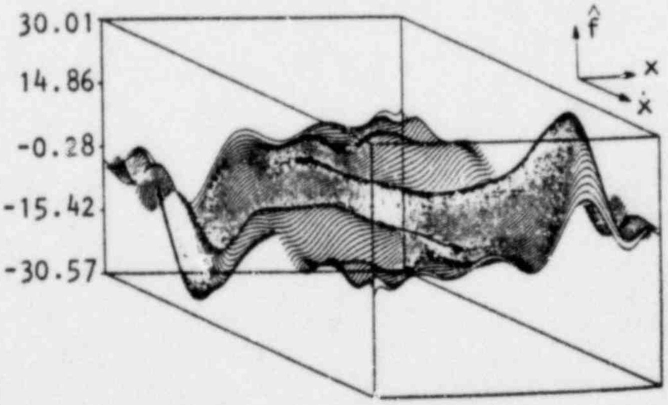
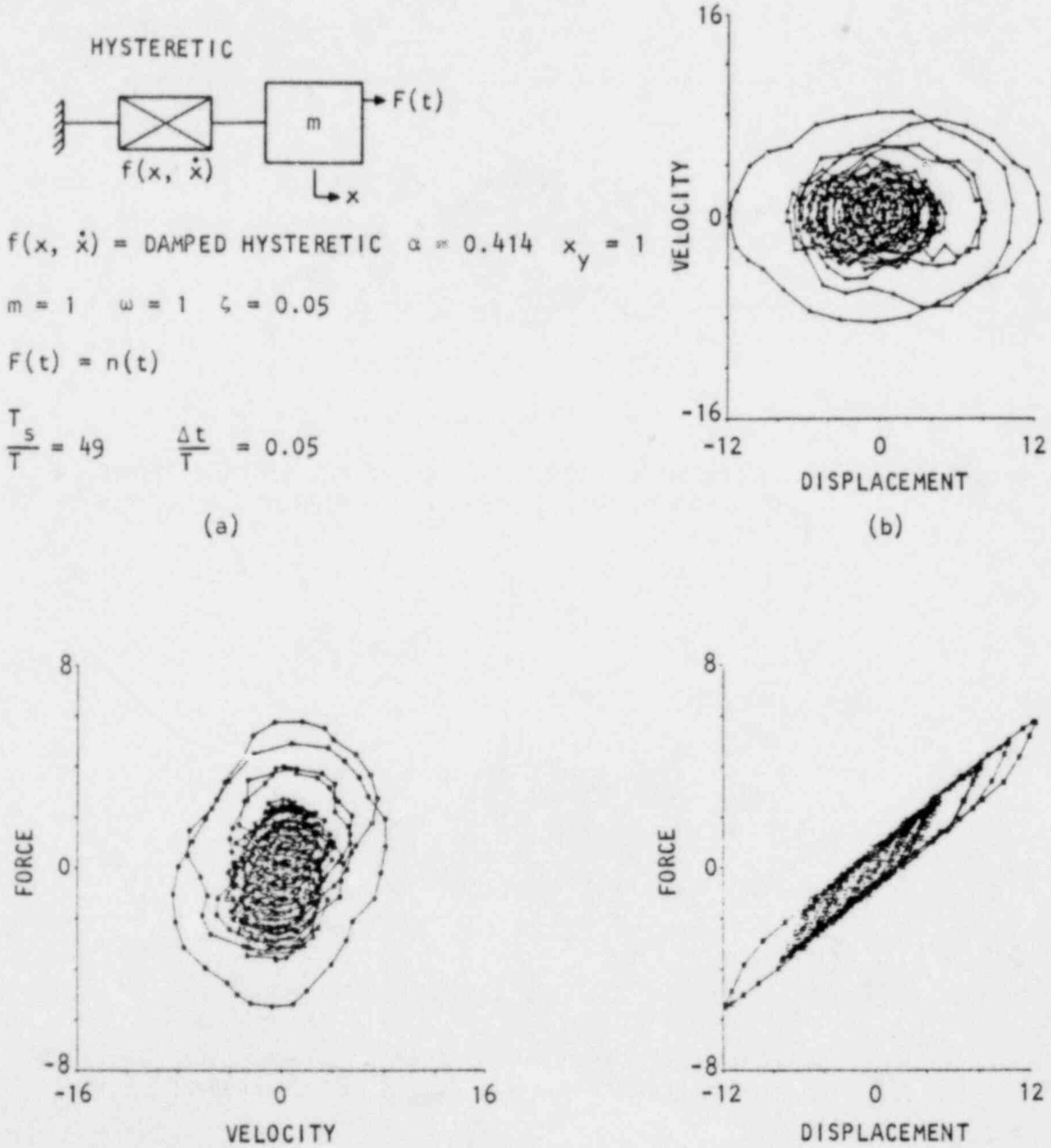


FIGURE A-25. LEAST-SQUARES CHEBYSHEV POLYNOMIAL APPROXIMATION $\hat{f}(x, \dot{x})$ TO $f(x, \dot{x})$ FOR THE VAN DER POL OSCILLATOR UNDER SWEPT-SINE EXCITATION



(a) (b)

(c) (d)

FIGURE A-26. STATE-VARIABLE PLOT FOR THE HYSTERETIC OSCILLATOR; $\sigma = 5$

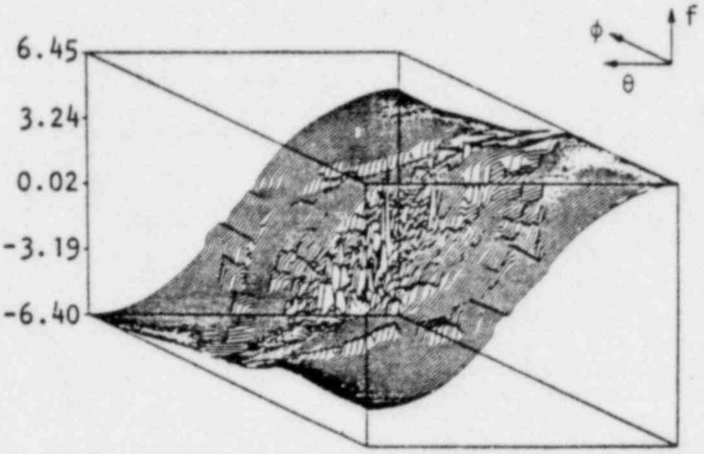


FIGURE A-27. INTERPOLATED VALUES OF $f(x, \dot{x})$ AT EQUIDISTANT POINTS IN θ AND ϕ FOR THE HYSTERETIC OSCILLATOR; $\sigma = 5$

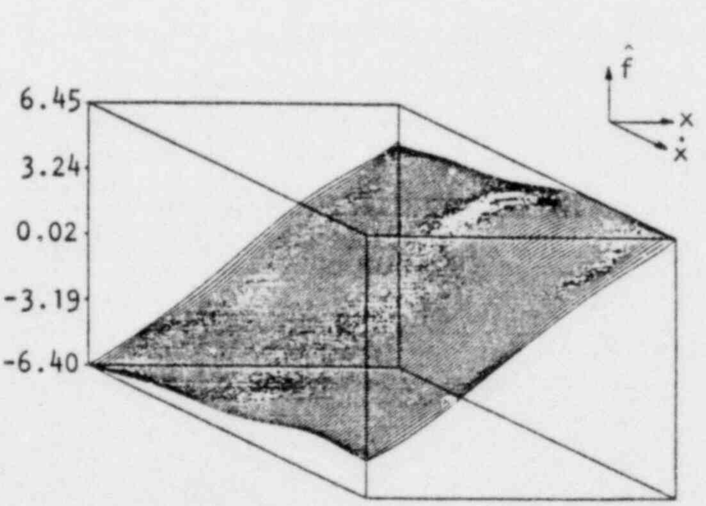


FIGURE A-28. LEAST-SQUARES CHEBYSHEV POLYNOMIAL APPROXIMATION $\hat{f}(x, \dot{x})$ TO $f(x, \dot{x})$ FOR THE HYSTERETIC OSCILLATOR; $\sigma = 5$

numerous details of the structure and all equipment interactions are automatically accounted for in the measurements.

b. The inertance functions are computationally handled in non-parametric form, i.e., modulus and phase or real and imaginary as a function of frequency or by inverse transformation to impulse functions (inertance as function of time). In this form, these functions represent a measure of the true system in that coupling exists (between modes) and in addition, coupled motions orthogonal to the axis of excitation also exist. The significance between in-axis and cross-axis (orthogonal) magnitudes can be observed in Figure A-4. This measured data was taken on a strongly reinforced concrete two-story earthquake-resistant building (460 ft long by 160 ft wide).

The structure or equipment is driven by exciters, sequentially at several locations, and measurements of motion (usually acceleration) are taken at selected points. The procedure is illustrated in Figure A-29, which depicts a containment structure. In order to simulate the distributed earthquake loads, the force generator is placed at various locations at the base of the structure. Motions are measured at several interior points of interest. However, if the structure responds elastically, the roles of the driver and the motion sensors may be interchanged. This role reversal is in accordance with the principle of reciprocity.

Where the structure is designed to respond nearly elastically for design criteria loads, data may be processed in the form of inertance (acceleration/force ratio) or transfer (output acceleration/input acceleration) as functions of frequency.

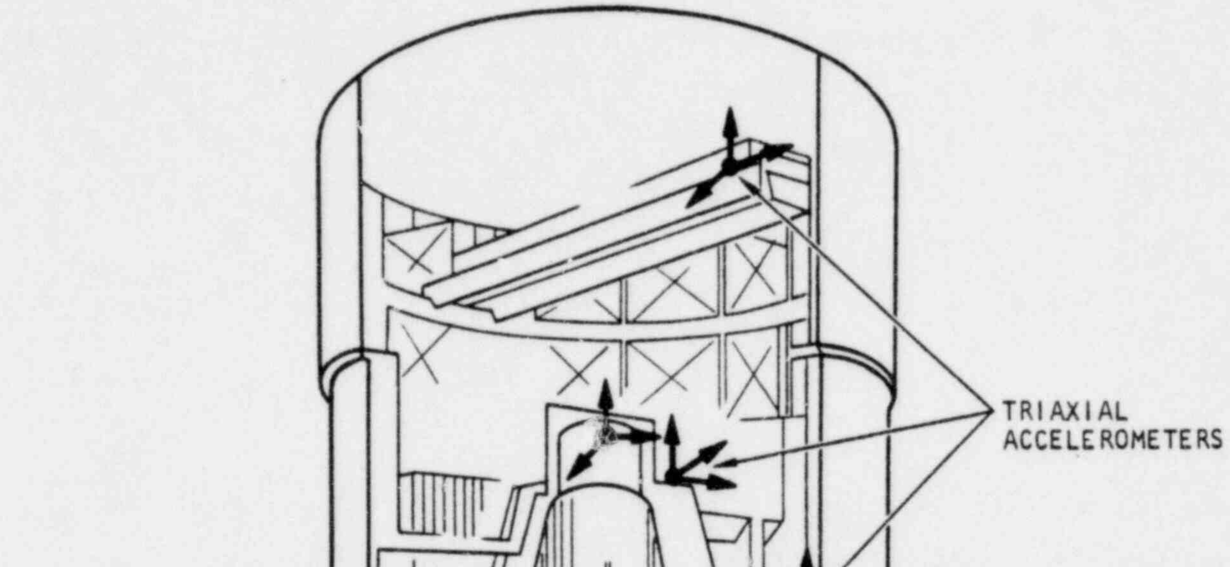


FIGURE A-29. SYSTEM IMPEDANCE MEASUREMENTS

The response prediction uses the transfer function data directly. This method is of special interest, since the resulting computed response includes actual coupled structural motions of the as-built structure. Since the structure is subject to distributed earthquake ground motion, the resultant structure response is the summation of the responses obtained by multiplying the transfer functions of the type shown in Figure A-2 by the Fourier transforms of the effective earthquake loads acting on the building. Equation 1 describes the total response of the structure:

$$\ddot{x}(f) = \sum_{i=0}^{N} \mathcal{A}_i(f) \;\; A_i \cdot P_i(f) \cdot Si_i(f) \;\; \exp(-j2\pi f\tau_i) \qquad \text{(A-12)}$$

where

$\ddot{x}(f)$ = Total response at a point in the building (in the frequency domain)

$\mathcal{A}_i(f)$ = i<u>th</u> transfer function from load point i to the response point

A_i = i<u>th</u> contributory area over which $P_i(f)$ acts

$P_i(f)$ = i<u>th</u> effective input load or motion

$Si_i(f)$ = i<u>th</u> engulfing function accounting for the fact that the load sweeps under the structure (where applicable)

τ_i = i<u>th</u> delay time between i<u>th</u> input point and arrival time of ground motion at the i<u>th</u> point (where applicable)

A simple inverse Fourier transformation of Equation (A-12) brings the frequency function into the time domain, i.e.,

$$\ddot{x}(t) = \int_{-\infty}^{\infty} \ddot{x}(f) \exp(i2\pi ft)df \qquad \text{(A-13)}$$

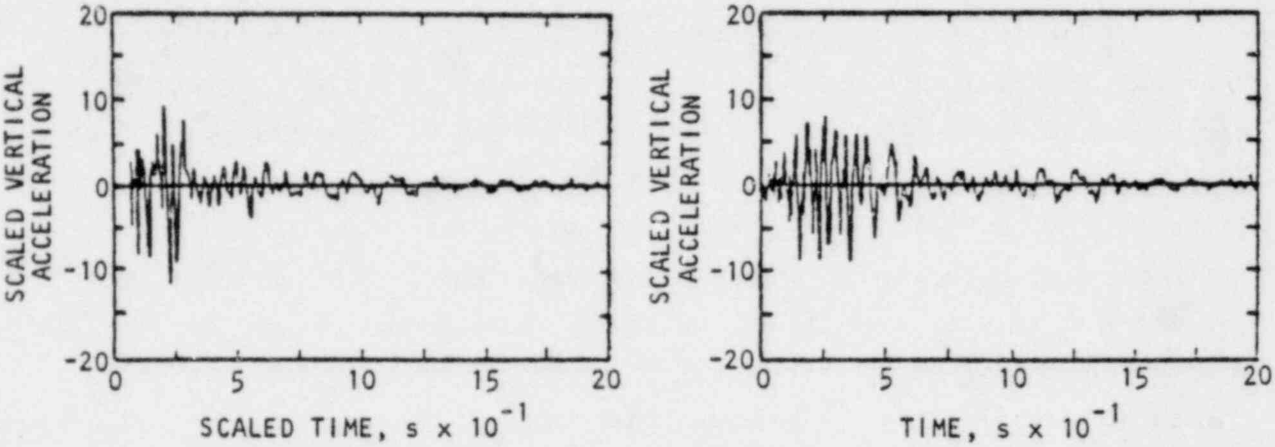
It is to be noted that the prediction method given here is based on a discrete number of transfer-function measurements, each acting over local areas. This sampling still provides an excellent means of motion prediction, as can be seen in Figure A-30 that compares motion prediction based on transfer-function measurements from a model structure with data records taken on the same structure during a high-explosive 500-ton TNT airblast and ground-motion field test. Also shown in the figure are response predictions by the transfer function technique for the prototype structure, which is 12 times larger. The comparison is considered to be quite acceptable, considering the early pioneering aspects of this effort.

The transfer functions used to predict the motion in Figure A-30 were obtained by slow sine sweeps in both model and prototype structures that are susceptible to distortions due to both mechanical and electrical noise. The changes in waveform due to noise in the phase measurements between Figures A-30b and A-30c were a result of improvements in signal-to-noise in testing the prototype (Fig. A-30c). Inertance functions of the model and prototype structures were used to scale the response motions of the model to prototype. This type of scaling was required rather than geometric scaling due to effects of internal equipment only in the prototype that reduced motion response (see Sec. A.1). As covered in Section A.1, current measurement and data processing methods have now reached such a state of precision as to allow general engineering usage.

Prediction of response motions of major structures using measured inertance functions must be modified where major and known nonlinearities exist. Overall, for a structure, the major nonlinearity is the soil or the structure/media interaction. This effect may be coupled to the above inertance function by use of separate stepwise linear measurements, restoring functions, or analytic expressions (LePage and Seely, 1950, and Blake and Belsheim, 1958).

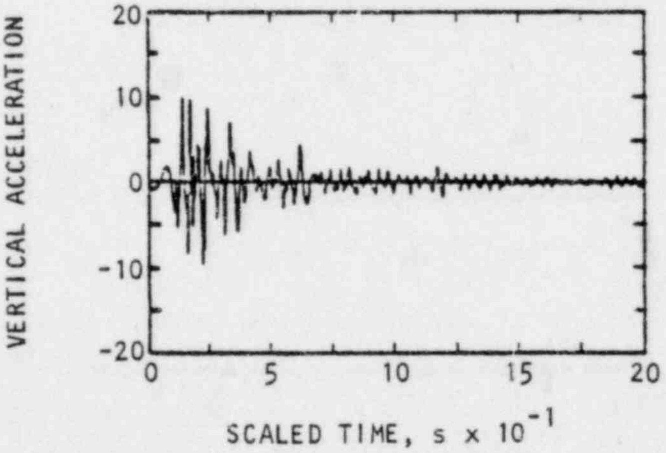
In previous sections, discussions were given to determine the free field ground earthquake motion for an SSE. A containment structure of a power plant loads the free field motion and alters it such that the resultant motion at the base of the structure reflects the dynamic properties of both the structure and the media. This modified earthquake motion at the base of the structure may be expressed in a general formulation as:

$$\underset{\substack{\text{free field}\\ \text{and}\\ \text{structure}}}{\ddot{X}(t)} \quad (=) \quad \underset{\substack{\text{free field}\\ \text{and}\\ \text{structure}}}{\ddot{X}(j\omega)} \quad = \quad \underset{\substack{\text{free}\\ \text{field}}}{\ddot{X}(j\omega)_{FF}} \left[\frac{1}{1 + \mathcal{A}_M / \mathcal{A}_S} \right] \tag{A-14}$$



(a) Measured model response from high explosive test (1/2 scale)

(b) Predicted model response based on inertance function measurement (1/2 scale)



(c) Predicted prototype (full scale) response based upon inertance function measurements

FIGURE A-30. COMPARISON OF ACCELERATION TIME HISTORIES FROM PROTOTYPE AND SCALED MODEL FIVE-STORY, HEAVILY REINFORCED PROTECTIVE CONCRETE STRUCTURE (125 FT HIGH, 194 FT WIDE, 210 FT LONG). INERTANCE FUNCTION OF MODEL AND PROTOTYPE WERE USED FOR SCALING THE MODEL TO THE PROTOTYPE where

$\ddot{X}(t)$ = Acceleration-time history of media and structure

$\ddot{X}(j\omega)$ = Acceleration-frequency spectrum of media and structure

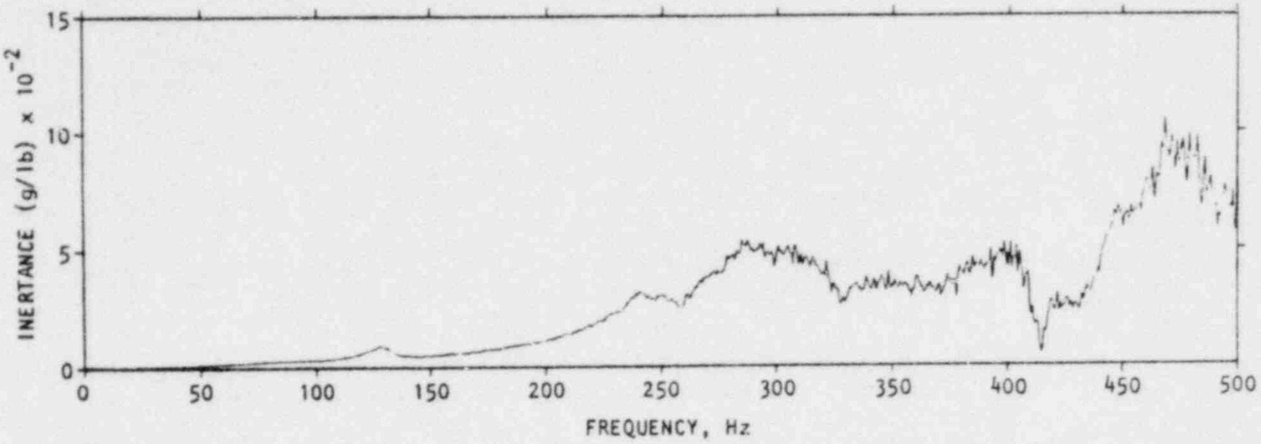
$\ddot{X}(j\omega)_{FF}$ = Acceleration-frequency spectrum of free field media (transformed from acceleration time-history of OBE/SSE)

$\mathcal{A}_M$ = Driving point inertance of free field media (stepwise linear or analytic nonlinear function)

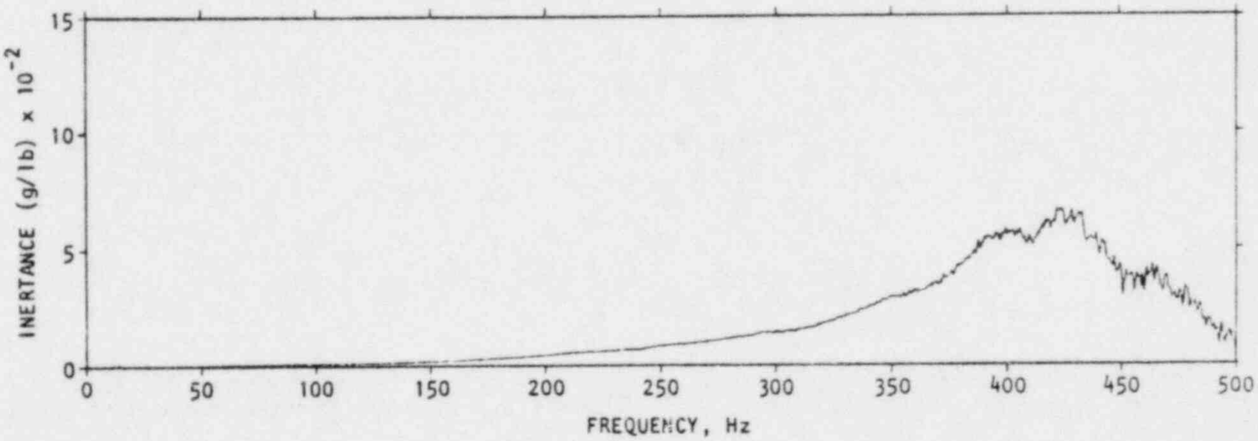
$\mathcal{A}_S$ = Driving point inertance of structure

The development of the media driving point inertance is of critical importance, particularly its characteristics as a function of location around the containment structure. Figure A-31 shows changes of soil characteristics as a function of depth from the surface for a constant input force of 1000 lbf random motion. Soil nonlinearity is given in Figure A-32 for a depth of 30 ft below the surface as a function of input force. Data in this figure can be used to develop "restoring functions" of a soil model as discussed in Section A.3.

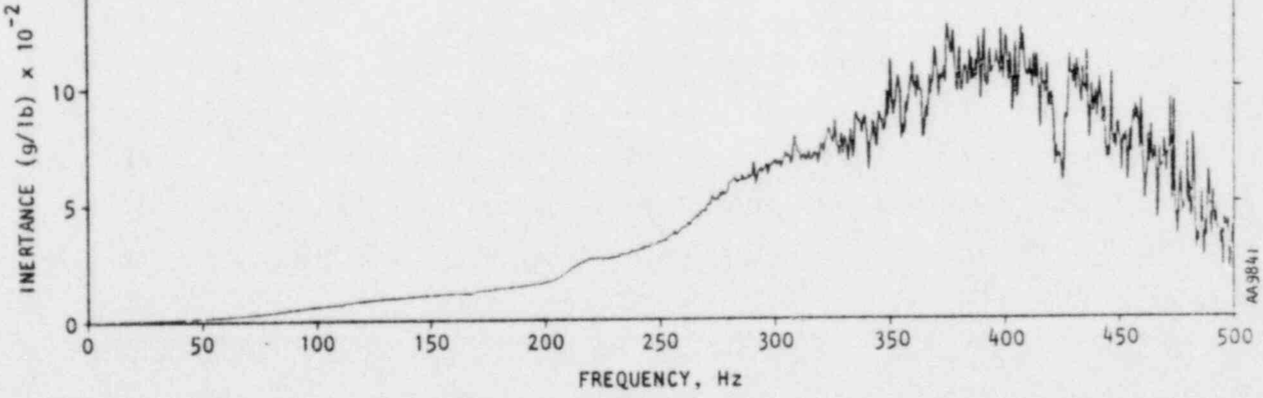
With the establishment of the effective base motion of the containment structure of the power plant from Equation (A-14), calculation of motions of the containment structure may proceed in accordance with Equations (A-12) and (A-13). Within the containment structure, motion at both the attachment location of equipment and of the equipment itself may be predicted. Separate handling is required for those equipments whose "linear" motions predict excursions into nonlinear regions as, for example, in piping and piping restraints. Here again, Equation (A-14) may be introduced and nonlinear formulations introduced either by stepwise measurements or analytic functionals to predict equipment motion. Motions of the primary structure at the locations of the piping constraints will be modified by the nonlinear motions of the equipment. However, if the ratio of the magnitudes of the driving point inertances of equipment and structure are less than 10 to 1, this attenuation effect on the main structure of the building may be ignored.



(a) Depth 0 ft

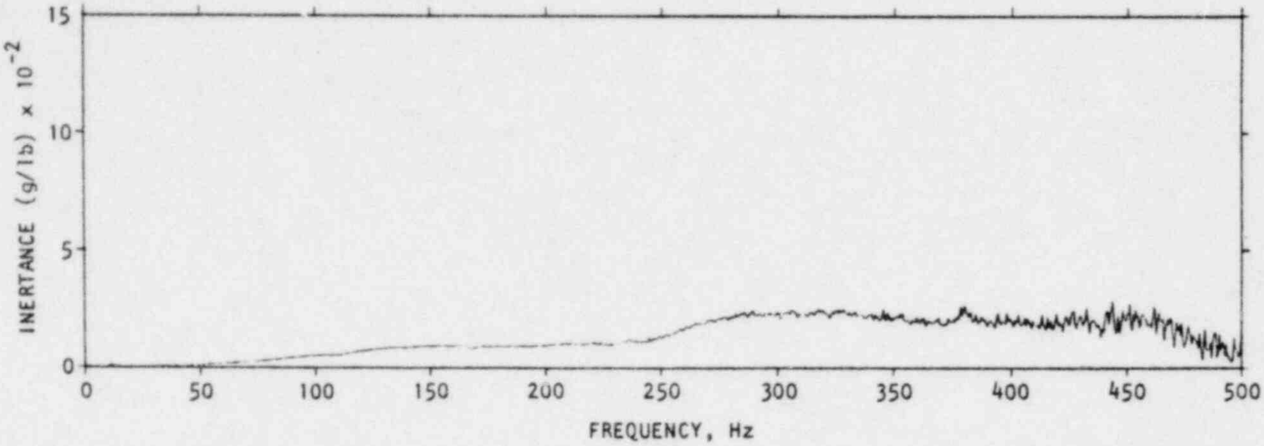


(b) Depth 5 ft

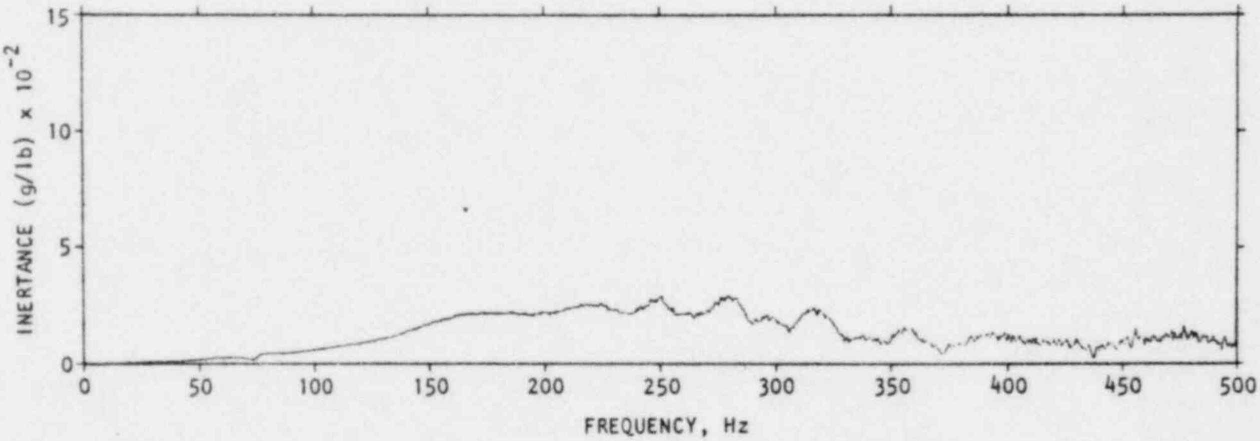


(c) Depth 11 ft

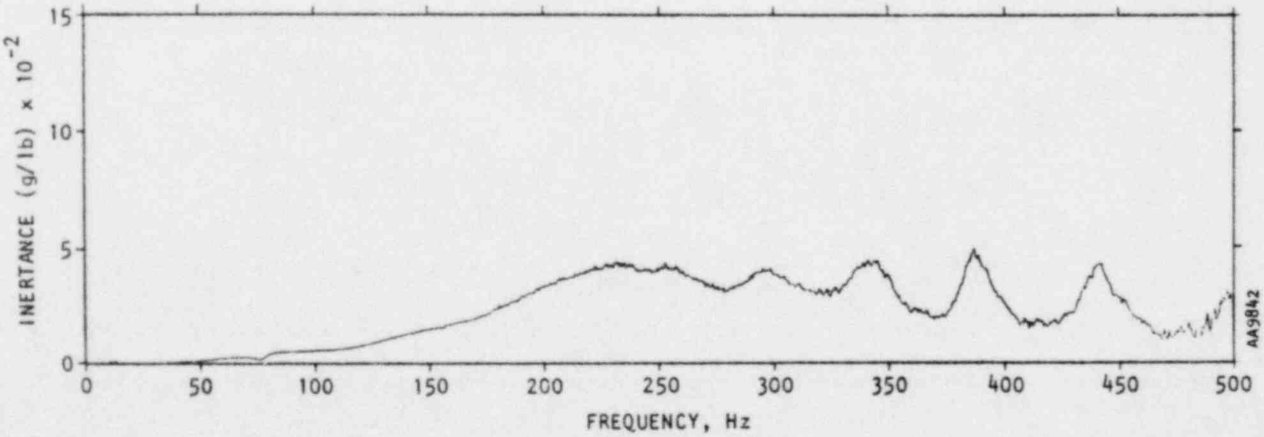
FIGURE A-31. HORIZONTAL DRIVING POINT INERTANCE IN SANDY SOIL AT SEVERAL DEPTHS BELOW SURFACE. INPUT FORCE 1000 LBF RANDOM



(d) Depth 12 ft

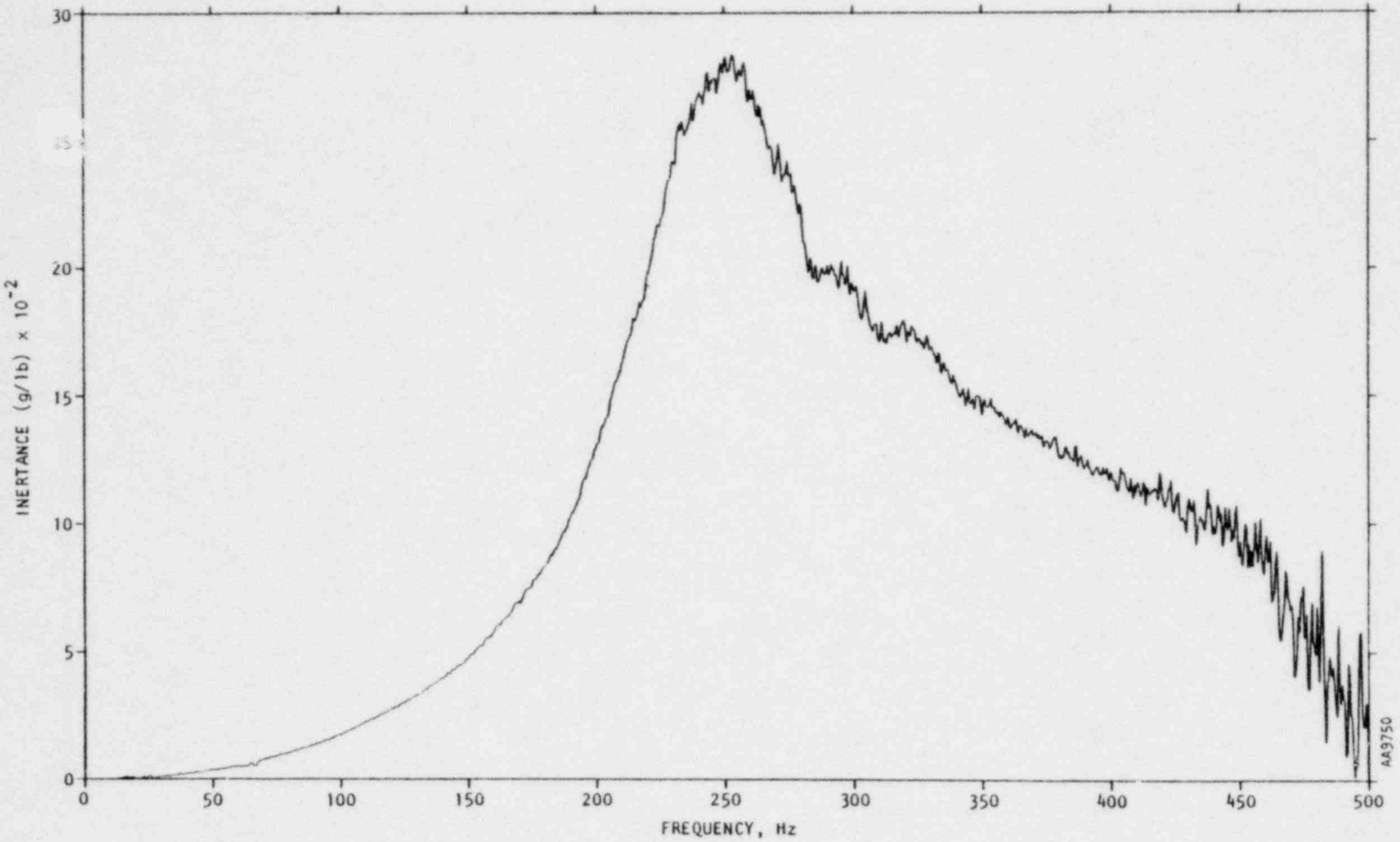


(e) Depth 18 ft



(f) Depth 19 ft

FIGURE A-31. (CONTINUED)



(g) Depth 30 ft

FIGURE A-31. (CONCLUDED)

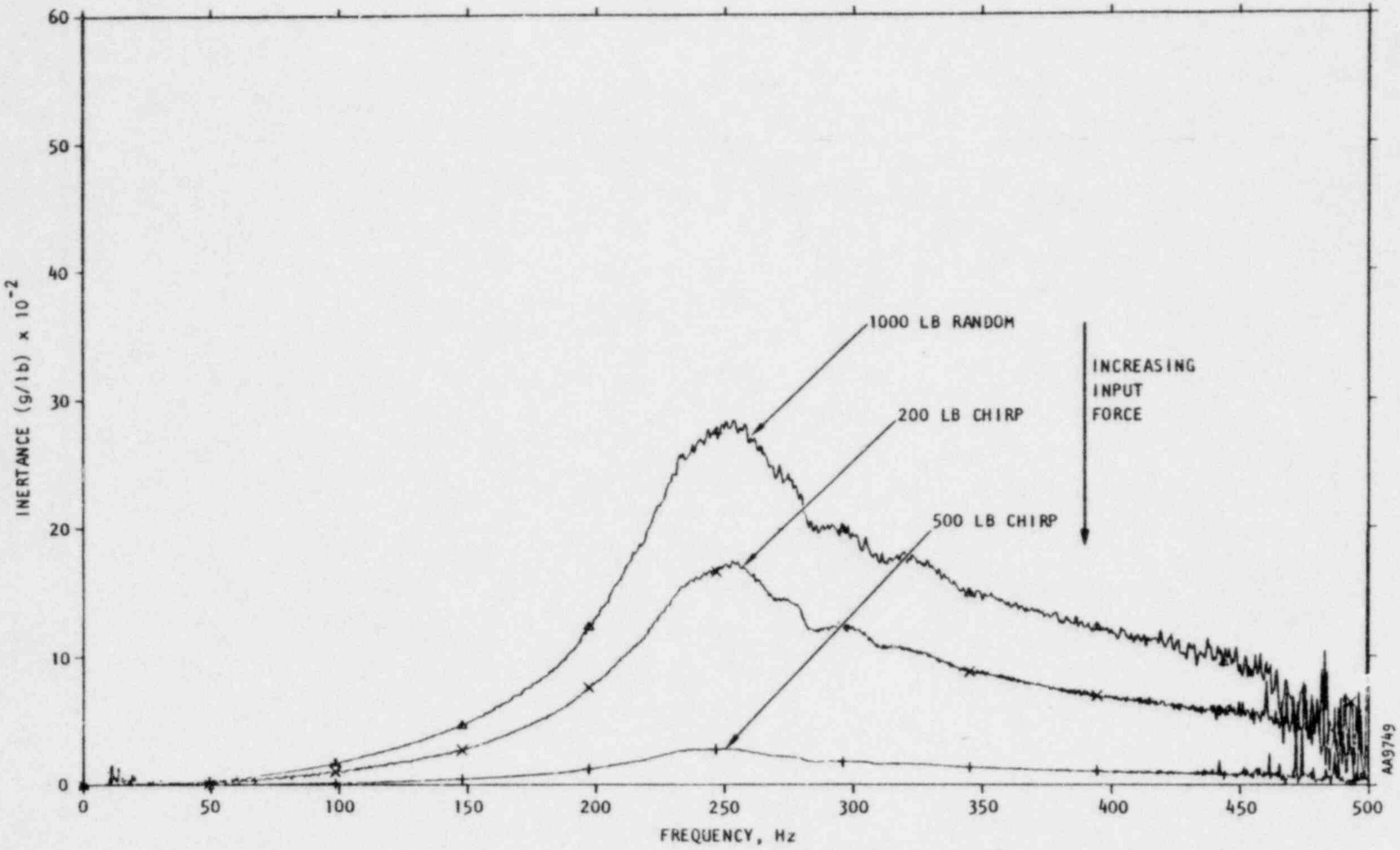


FIGURE A-32. HORIZONTAL DRIVE POINT INERTANCE AT A DEPTH OF 30 FT IN SANDY SOIL AS A FUNCTION OF INPUT FORCE

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The purpose of the study is to develop a program plan to provide assurance by physical demonstration that nuclear power plants are earthquake resistent and to allow nuclear power plant operators to (1) decide whether tests should be conducted on their facilities, (2) specify the tests that should be performed, and (3) estimate the cost of the effort to complete the recommended test program.

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