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VERIFYING SEISMIC DESIGN
OF NUCLEAR REACTORS
BY TESTING

Volume 2: Appendix
Theoretical Discussions

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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

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

- 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:

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

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

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

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

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Cross-axes inertance as a function of frequency.

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

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

FIGURE A-3. CROSS-AXES SYSTEM FUNCTION

A-5

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)

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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:

$$r(t) (=) R(\omega) = \mathcal{A}(\omega) F(\omega) \quad (A-1)$$

or

$$r(t) = \int_0^t h(t - \tau) f(\tau) d\tau \quad (A-2)$$

where

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

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

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

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

$r(t)$ = 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

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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 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 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

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

A-10

FIGURE A-6. EXAMPLE OF INERTANCE MAGNITUDE AFFECTED BY NOISE

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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 $-\pi$ 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:

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

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:

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

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FIGURE A-7. PHASE MEASUREMENTS WITH HIGH NOISE CONTAMINATION

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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)

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

When $\gamma_{xy}^2(f) = 0$ at a particular frequency, $x(t)$ and $y(t)$ are said to be incoherent (uncorrelated). When $\gamma_{xy}^2(f) = 1$ 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)

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(a) Driving point inertia measurement with spring isolated equipment platform connected to roof

(b) Driving point inertia 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

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(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:

$$\frac{1}{\mathcal{A}_L} = \frac{1}{\mathcal{A}_F} + \frac{1}{\mathcal{A}_E} \quad (\text{A-5})$$

$$\mathcal{A}_E = \frac{\mathcal{A}_F \mathcal{A}_L}{\mathcal{A}_F - \mathcal{A}_L} \quad (\text{A-6})$$

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:

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

where

- $\ddot{X}_{\text{load}}(t)$ = Acceleration-time history of equipment and facility
- $\ddot{X}_{\text{load}}(j\omega)$ = Acceleration-frequency spectrum of equipment and facility
- $\ddot{X}_{\text{no load}}(j\omega)$ = 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 $[\ddot{X}(j\omega)/F(j\omega)]$ of facility

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

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

Floor	Scale Factors				Difference (Reference Geometric)	
	Inertance		Geometric			
	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

Floor	Acceleration Response Scaling				Difference (Reference Geometric)	
	Inertance		Geometric		Fourier Magnitude, λ^3/ab^2	Time History & Shock Spectra, λ^3/ab^2
	Fourier Magnitude, λ^3/ab^2	Time History & Shock Spectra, λ^3/ab^2	Fourier Magnitude	Time History & Shock Spectra, 1/)		
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

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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 $\left[\frac{\ddot{X}}{F} (j\omega) \right]$.

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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:

$$\begin{array}{c}
 \text{Lateral Direction} \\
 \begin{bmatrix} \ddot{x}_{H1} \\ \vdots \\ \ddot{x}_{Hn} \end{bmatrix}
 \end{array}
 =
 \begin{array}{c}
 \text{Longitudinal Direction} \\
 \begin{bmatrix} \ddot{x}_{HL1} \\ \vdots \\ \ddot{x}_{HLn} \end{bmatrix}
 \end{array}
 \begin{array}{c}
 \text{Vertical Direction} \\
 \begin{bmatrix} \ddot{x}_{V1} \\ \vdots \\ \ddot{x}_{Vn} \end{bmatrix}
 \end{array}
 =
 \begin{array}{c}
 \text{Structural Impulse Function Matrix} \\
 \begin{bmatrix} h_{H1} & & & \\ & \ddots & & \\ & & h_{Hn} & \\ & & & h_{H1/HL1} & & h_{H1/V1} \\ & & & & \ddots & \\ & & & & & h_{HL1} & & \\ & & & & & & \ddots & \\ & & & & & & & h_{V1} & & \\ & & & & & & & & \ddots & \\ & & & & & & & & & h_{Vn} \end{bmatrix}
 \end{array}
 \begin{array}{c}
 \text{Input Pulse Generators} \\
 \begin{bmatrix} F_{H1} \\ \vdots \\ F_{Hn} \\ F_{HL1} \\ \vdots \\ F_{HLn} \\ F_{V1} \\ \vdots \\ F_{Vn} \end{bmatrix}
 \end{array}
 \quad (A-8)$$

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%.

$$\text{erf} = \frac{\int_0^t (\ddot{x}_{\text{Ref.}} - \ddot{x}_{\text{Pulsed}})^2 dt}{\int_0^t \ddot{x}_{\text{Ref.}}^2 dt} \quad (\text{A-9})$$

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

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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 identification 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

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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

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

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.

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FIGURE A-20. BLOCK DIAGRAM FOR NONPARAMETRIC SYSTEM IDENTIFICATION

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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

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

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

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

(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

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VAN DER POL

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

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

$$F(t) = F_0 \sin \Omega(t) t$$

$$F_0 = 10 \frac{\Omega(0)}{\omega} \approx 0.5 \quad \frac{\Omega(T_s)}{\omega} = 1.5$$

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

(a)

(b)

(c)

(d)

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

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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

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

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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.

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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:

$$\ddot{x}(f) = \sum_{i=0}^N \dot{w}_i(f) A_i \cdot P_i(f) \cdot S_{i_i}(f) \exp(-j2\pi f \tau_i) \quad (A-12)$$

where

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

$\dot{w}_i(f)$ = ith transfer function from load point i to the response point

A_i = ith contributory area over which $P_i(f)$ acts

$P_i(f)$ = ith effective input load or motion

$S_{i_i}(f)$ = ith engulfing function accounting for the fact that the load sweeps under the structure (where applicable)

τ_i = ith delay time between ith input point and arrival time of ground motion at the ith point (where applicable)

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

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

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

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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:

$$\begin{array}{ccccc} \ddot{X}(t) & (=) & \ddot{X}(j\omega) & = & \ddot{X}(j\omega)_{FF} \left[\frac{1}{1 + j\eta/\sqrt{s}} \right] \\ \text{free field} & & \text{free field} & & \text{free field} \\ \text{and} & & \text{and} & & \\ \text{structure} & & \text{structure} & & \end{array} \quad (A-14)$$

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(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)
- $\cdot N_H$ = Driving point inertance of free field media
(stepwise linear or analytic nonlinear function)
- $\cdot N_S$ = 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.

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(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

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FIGURE A-31. (CONTINUED)

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(g) Depth 30 ft

FIGURE A-31. (CONCLUDED)

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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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