SEISMIC QUALIFICATION BY SHAKE TABLE TESTING

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SYNOPSIS

This paper examines the seismic qualification of equipment for nuclear power plants using shake table test methods. The response of a nuclear reactor structure to an earthquake is used to present the concept of floor response spectra for various equipment locations throughout the structure. The floor response spectra are used as the basis for developing shake table tests to examine the functional capabilities of reactor safety system components mounted at these locations. Current test methods are discussed and certain advantages and limitations are pointed out. A case history illustrates the use of single frequency testing in the seismic qualification of a diesel engine. Throughout the paper comments are made on problems currently being faced in providing meaningful qualification tests and on possible areas and directions for future research.

RESUME

Cette communication présente la manière de certifier un type d'équipement pour une centrale nucléaire, à cause de l'effet sismique, en utilisant des méthodes adaptées aux tables vibrantes. La réponse de la structure sous l'effet d'un tremblement de terre sert de base pour calculer les réponses spectrales à différents niveaux. Ces réponses spectrales servent à leur tour pour le développement des méthodes adaptées aux tables vibrantes. L'objectif est de promouvoir la sécurité de ces équipements à différents niveaux. Des commentaires et suggestions sont fournis pour le cas d'un moteur qui doit satisfaire les exigences aséismiques.

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INTRODUCTION

To demonstrate the functionality of certain nuclear power plant components in an earthquake environment, shake table tests are performed to expose a test specimen to simulated seismic events. This paper examines current testing techniques for the seismic qualification of mechanical and electrical equipment and, based upon testing experience at McMaster University, outlines how seismic qualification test programs are developed and conducted (6). Throughout the paper, attention is focussed on some of the problem areas of testing and on areas where the authors feel that future research would be beneficial.

The discussion is devoted to three major topics. The first section is concerned with the earthquake environment which an equipment installation will experience, in order that subsequent discussions of laboratory simulations can be related to real events. The current state-of-art as reflected by the guidelines and recommended practices of CSA N289.4 (draft) (1) and IEEE 344-1975 (2) are then discussed with an emphasis on test methods (especially the single frequency approach) and the authors' opinions of some of the inconsistencies and shortcomings of present guidelines. A final section presents a case study of a seismic test on an 80 horsepower diesel engine illustrating various aspects of the seismic qualification test procedure.

ELECTRICAL AND MECHANICAL EQUIPMENT IN AN EARTHQUAKE ENVIRONMENT

The development of a valid seismic qualification program whether by test, analysis or a combination of both depends upon a realistic evaluation of the seismic environment which the equipment would be expected to experience in a nuclear power plant installation. For analysis purposes the environment is described mathematically or numerically. In test applications the simulated seismic environment is defined by displacement and acceleration levels of the shake table motion which requires a practical consideration of how appropriate excitations can be defined and applied to the equipment.

The response of electrical and mechanical equipment to earthquakes is often a secondary response to the overall nuclear power plant response. That is, a mathematical model of the reactor-equipment system requires at least two degrees of freedom as shown in Fig. 1. First of all, as the earthquake ground motions become significant the reactor structure begins to respond to the broadband random seismic motion. From a dynamic analysis of the lumped mass model the time-history response at a given location can be evaluated. This motion is then subjected to a further analysis to produce a floor response spectrum (FRS), which is generally an amplified and narrower-band version of the ground motion spectrum, emphasizing the structure's natural frequencies. Larger amplifications are seen in the floor motion time-histories and spectra for equipment locations at higher elevations within the reactor structure. The result is that on upper floors the equipment may experience accelerations several times that of the earthquake ground motion. Compounding this problem of amplification, the floor motion may tend to a quasi-harmonic state at one of the structural natural frequencies. Thus, the seismic environment at equipment locations will usually impose a more severe loading on the equipment than if it were installed at ground level.

The process just outlined for the development of floor response spectra is illustrated in Fig. 2. The lumped mass model is typical of a reactor containment structure and the time history shown alongside the model was used for input for a dynamic analysis. The floor response time histories and spectra shown beneath the model for two selected locations clearly illustrate structural amplification and filtering effects. Due to the uncertainties in foundations and structural parameters, particularly at the initial stages when equipment specifications are developed, the actual structural frequencies may vary over quite a range. Consequently, in order that the equipment may be qualified for any actual structure, the computed floor response spectrum for a particular location is broadened and smoothed to develop the design FRS. Typical design FRS curves are also shown in Fig. 2.

Once a FRS appropriate for a given equipment location has been obtained, the next step is a laboratory simulation of this motion. Providing mounting conditions similar to those at the installation site for small, lightweight components is generally not a problem. However, when test specimens become very massive, or have a large spatial array (i.e., cabling networks, rows of electrical panels, etc.) mounting can become very difficult. The authors' approach in these situations has been to attempt to design a rigid shake table mounting assembly and evaluate its performance under dynamic conditions prior to testing. If any mounting compliance is detected and cannot be suitably removed then an allowance is made in the levels of input motion used and in the interpretation of test results. It is of interest to note that qualification specifications often implicitly assume a rigid equipment mounting in the nuclear power plant and so this is what test laboratories strive to achieve. The authors have found that in some instances, the assumed installation may not have as rigid a mounting as the test specimen on the shake table. Therefore, some degree of mounting compliance may be tolerable for certain tests as it is not really a departure from actual service conditions. The area of laboratory simulation of equipment installations has received relatively little investigation and future research may lead to better ways of determining a realistic laboratory set-up.

SHAKE TABLE TEST PROCEDURES

The many types of vibratory input motion that may be used to test a component can be classified into two broad categories depending upon the frequency content of the input waveform. The first category involves single frequency input signals. The second grouping is a more complex type of input, a multi-frequency waveform which may be either a real or an artifically generated time history. Both of these methods may be used to test equipment to either a proof level (exposure to a specified level of input) or a fragility level (taking the test specimen to failure, to evaluate the ultimate seismic capability) (7). While fragility testing provides a measure of the seismic "withstand" capability, the expense involved in failing a specimen is usually unwarranted as there may not always be a significant gain of information above that of the proof test. Consequently, most seismic qualification relies upon the proof test method.

Single Frequency Methods

The distinguishing characteristics of single frequency tests is a series of short-duration inputs applied at discrete intervals over the entire frequency spectrum. It is the authors' contention that single frequency test procedures are appropriate for a much wider set of conditions than have generally been accepted. Even for broadband seismic ground motion and complex structural systems, the FRS tend to be narrow-band (see Fig. 2). Generally a broad-band spectrum is only obtained by artificially broadening a narrow-band spectrum to account for certain structural, site and other variations and the resulting broad-band spectrum is not really representative of any real earthquake event (5). It appears then, that opposition to a wider use of single frequency techniques may be based upon the nature of the broad-band FRS used for the test rather than on a more meaningful basis taking into account how the broad-band spectrum was actually obtained in the first place.

Four basic types of single frequency techniques are suggested as being appropriate for testing by CSA N289.4 (draft) and IEEE 344-1975. These waveforms are illustrated in Fig. 3 (a-d) and are discussed in the following.

Sine sweep test--This test motion involves an excitation of constant acceleration or displacement with a continuously varying frequency from 0.5 or 1.0 Hz to 33 Hz. A slow sweep rate, usually 2 octaves per minute, allows sufficient time for all components of the test specimen to respond in a quasi-resonant manner. Consequently, this test is most often used as an exploratory technique for evaluating a specimen's dynamic characteristics prior to the full qualification tests.

Continuous sine test--In this test the equipment is excited by an application of a regulated number of cycles of pure sinusoidal shake table motion. As the input is continuous harmonic, there is potential for large amplifications in regions where the equipment's natural frequency is close to the shake table frequency. Current recommendations specify a minimum of 5 to 7 full cycles or 2 seconds of motion, whichever produces the longer duration. In evaluating the test response spectrum (TRS) using 5-7 cycles of motion the spectral amplification for a 1% damped single-degree-of-freedom system will be about 13, well below the resonant amplification of 50 (refer to Fig. 4). In order to provide qualification across the entire frequency spectrum a series of inputs are used, generally spaced at one-half to one-third octave intervals between 0.5 Hz and 33 Hz.

The authors have conducted several seismic qualification test programs based upon the above two test methods, using a sine sweep exploratory test followed by full qualification using a duration limited continuous sine input. One of these test programs is discussed in the last section of this paper.

Decaying sine test--The peak amplitude and the decay rate of the input signal are used to regulate the response. The input motion, similar in appearance to a free vibration decay (see Fig. 3c), has as its limiting case for very small decay rates a continuous sine excitation. A useful application of this test is in the simulation of low-cycle fatigue effects since the decay rate can be adjusted to allow for numerous cycles of motion without producing an excessive amplification. To accomplish fatigue simulation using a continuous sine input would require impracticably small table displacement levels to compensate for the large amplifications.

Sine beat test--One or more sine beat vibrations as shown in Fig. 3(d) are applied to the test specimen. The number of cycles of test frequency motion per beat controls the level of dynamic amplification. CSA N289.4 recommends the use of 5 cycles per beat which will produce the following magnification factors: 8.6 for 1% damping; 7.6 for 2% damping; 5.6 for 5% damping. Fatigue effects can also be simulated by using a series of beats with sufficient pauses between each to avoid a super-position of response from one beat cycle to the next.

Multi-Frequency Methods

Current standards and guidelines recommend the use of multi-frequency test methods when the ground motion has not been strongly filtered and still retains the broad-band characteristics of the earthquake. As discussed in the previous section, the conservatism introduced through spectra enveloping and broadening may lead to quite an unrealistic test requirement and may adversely affect a manufacturer's ability to qualify his equipment, or it may lead to an unnecessary degree of overdesign and expense (4).

Unless a time-history is specified by the user or a real earthquake event is used as a basis for test, a synthetic multi-frequency record must be created which will envelope the user specified required response spectrum (RRS). The most common technique for developing a synthetic record is to use a filtered random noise source to create a first trial record. Progressive modifications are then introduced until its response spectrum (the test response spectrum (TRS)) closely approximates or envelopes the RRS. Since random signals are used to create the TRS, an infinite number of time-histories could be synthesized all of which would satisfy the RRS, although each would have a different TRS. Presumably then, a component could be qualified using any of these artificial records. At this point current specifications provide no further guidance on the use of these randomly generated records, nor do they indicate how tests using different spectrum compatible time histories can be interpreted on a consistent basis. Since a response spectrum does not retain important information on phasing and time intensity relationships it is quite conceivable that a test specimen may fail using one synthetic record and yet be acceptable when tested with another, randomly generated time-history (4). The development of meaningful multi-frequency test methods and guidelines to the interpretation of equipment response during these tests is an area where significant research efforts are required.

Proof vs. Fragility Testing

The current versions of CSA and IEEE standards express the idea of a proof test as being used to qualify equipment for a particular application or to a specified vibratory input as defined by the user. The "proof" of qualification at this level is usually taken as the satisfactory performance of the equipment, however such a test does not provide any indication of the margin between the proof level and the ultimate (fragility) failure level. Additionally, there is no consideration given to the possibility of permanent, undetectable damage occurring during the test program. Damage of this type may place the component on the borderline of failure such that the occurrence of even a single earthquake below test levels may be sufficient to fail the so-called "qualified" component when it is installed in a power plant. The single and multi-frequency methods discussed previously are all appropriate for proof testing. Research into the characterization of test motions and equipment response to these motions should lead to a more meaningful basis on which proof test levels can be established and how these may be realistically simulated on shake tables.

Fragility testing is much less common than proof testing. The authors have had experience in one fragility test of the structural framework for an electrical panel assembly. A resonant search by a standard sweep test revealed two predominant natural frequencies [one torsional, one lateral] which were then used as the basic input frequencies for the fragility test. Resonant response curves were obtained by inputting increasing accelerations to the equipment at several frequencies below and above each natural frequency until noticeable damage occurred to the equipment frame. From the resonant curves information on the non-linear behaviour of the component at large strain levels was obtainable, including changes in damping and amplification levels. A difficult interpretation to make in this type of test is the reason for component failure, as two major factors are involved. Did the failure occur because of the large response levels, or was failure a fatigue problem stemming from repeated testing? Usually it will be difficult if not impossible to separate these two factors. Careful observation of the component after each level of test may reveal signs of fatigue. On the other hand, tests on brittle components such as ceramic insulators will leave little doubt as to establishing failure due to high input levels.

At the present time little consideration has been given to means of evaluating equipment functionality. The capability of a relay switch to function during shaking is relatively easy to ascertain by measurement of power continuity. Difficulties arise when a component's function is dependent upon several other equipment functions such as in valve and pipe networks or in multi-component electrical control units. As an example case, shake table testing may demonstrate that a mechanical valve has a proven seismic "withstand" capacity when tested individually (i.e., the proper opening and closing is not impaired by shaking). In a complete network however, its proper operation will be meaningless unless the fluid can reach the valve and the electronic sensors function properly in signalling it to open or close. Thus, substructuring a system or network for purposes of testing must be done with extreme care in order that tests of individual components remain valid for the whole system.

CASE STUDY ON THE SEISMIC QUALIFICATION OF A DIESEL ENGINE

The safe shutdown of a nuclear power plant requires that a continuous supply of cooling water be available to prevent an excessive heat build-up. In the CANDU system, diesel engines are used as emergency stand-by units to drive water coolant pumps in the event of an interruption in the electrical supply to regular pumping units. Since an earthquake is one situation where a shutdown may be required, the diesel engines must be seismically qualified to determine their operational performance under simulated seismic shaking conditions. To provide the required seismic tests for a diesel engine of this type a test program was undertaken by McMaster University under contract to the engine supplier (3).

Shown in Fig. 5 is the diesel engine mounted on the shake table. In each of the three orthogonal test directions (two horizontal, one vertical) the engine was bolted through its normal mounting holes directly to a one-inch steel plate assembly on the table (a separate shake table system was used for the vertical tests). Nine accelerometer locations were selected for preliminary test runs. On the basis of the exploratory runs, three locations were instrumented with accelerometers for the final tests (arrows on Fig. 5).

The input spectrum for the exploratory sweep test and the sweep response at accelerometer location 1 are shown in Fig. 6 with resonant frequencies indicated by peaks in the sweep trace. The levels of excitation were selected to keep the sweep spectrum well below the FRS over most of the frequency range. Due to limitations on the shake table control system, the exploratory sweep test was performed in 5 constant displacement segments rather than in a constant acceleration mode. This segmentation of the sweep avoided the high accelerations associated with increasing frequency at a fixed displacement.

The actual seismic qualification testing was done using short duration, single frequency sinusoidal inputs. The 1% damped FRS provided by the engine supplier was the basis for the test levels and is shown in Fig. 7. Following current recommended practice the input frequencies were selected at approximately one-third octave intervals over the range 1-33 Hz. The results of the exploratory sweep tests were used at this stage to avoid selecting any test frequencies coincident with a major engine resonant frequency. Although test inputs were not selected at resonant frequencies, the TRS produced at neighbouring frequencies did envelope the RRS at the resonant frequencies. The basis for this decision was to avoid overtesting and cyclical fatigue effects due to an unrealistically amplified engine response.

The full qualification tests were to employ single axis testing hence the RRS was set at 1.5 times the FRS to allow consideration for possible directional coupling effects in the equipment response. This RRS constituted the response requirement to be met during testing and, according to the user's specifications, the RRS was to be completely enveloped by the TRS. Using the magnification curves shown in Fig. 4 the table motion was chosen to keep the entire TRS above the RRS. For example, to achieve a TRS level of 1.8" at 2 Hz using 6 cycles of input a table displacement of 1.8/13 = 0.14" was required, where 13 is the magnification factor for 6 cycles as indicated on Fig. 4. The complete set of spectral curves for the test program is shown in Fig. 7.

The test program was completed in 3 orthogonal directions during which the diesel engine continued to perform satisfactorily. After the complete test series in each direction the engine was stopped then restarted to demonstrate its final functional capability. On the basis of its satisfactory performance the engine was certified to have performed adequately under current seismic qualification test requirements.

SUMMARY AND CONCLUSIONS

This paper has reviewed current methods of shake table testing of equipment, primarily for the nuclear power industry and has illustrated the application of some of these methods through a case study of an actual seismic qualification test program. The discussion began with a description of the earthquake environment to which mechanical and electrical equipment may be subjected. Single frequency tests were discussed in some detail and shown to have validity in many cases, especially where the means of selection and use of an appropriate multi-frequency input is unclear. Finally, one of the authors' seismic qualification testing programs at McMaster University was used in demonstrating the application of current test specifications, the development of exploratory and full scale tests and the subsequent certification of seismic qualification.

Seismic qualification is a relatively new area of earthquake engineering. Its rapid expansion and increasing importance has resulted from the stringent safety requirements set by the Atomic Energy Control Board in Canada, the Nuclear Regulatory Commission in the U.S. and by other foreign agencies, and also from demands by utility service companies for earthquake resistant equipment installations. Four areas for research have been emphasized; (1) an evaluation of testing system components separate from the whole system in which they are intended to function, (2) the characterization of seismic motions in a structural system as complex as a nuclear power plant, (3) investigation of the equivalence amongst the several test methods proposed by current standards, and (4) research into fragility testing, how such tests should be performed, and how the results should be evaluated. Future research in these areas is necessary in order that current standards and guidelines can be critically examined and improvements made based upon rational and consistent grounds.

ACKNOWLEDGEMENTS

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ABBREVIATIONS USED IN THE TEXT

FRS - floor response spectrum: a spectral description of the motion of the floor at an equipment mounting location.

RRS - required response spectrum: the response levels to be met during the test, as defined by the user.

TRS - test response spectrum: response of a single degree of freedom system to the test levels of shake table motion.

SI CONVERSIONS

1 in. = 0.0254 m
1 ft. = 0.3048 m
1 lb. = 0.4536 kg

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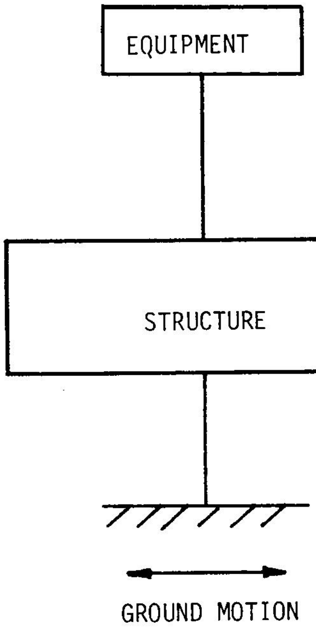

Fig. 1 Simple Dynamic Model of a Reactor-Equipment System

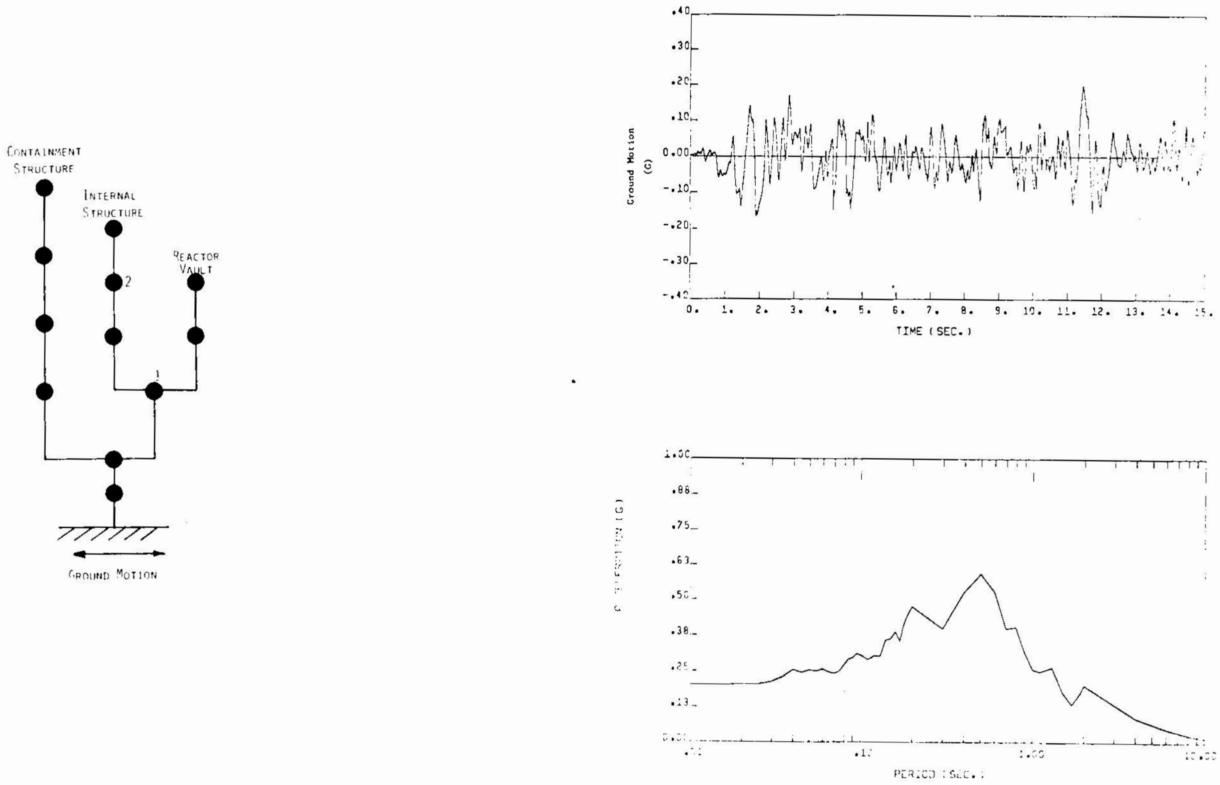

Fig. 2 Floor Response in a Typical Reactor Model

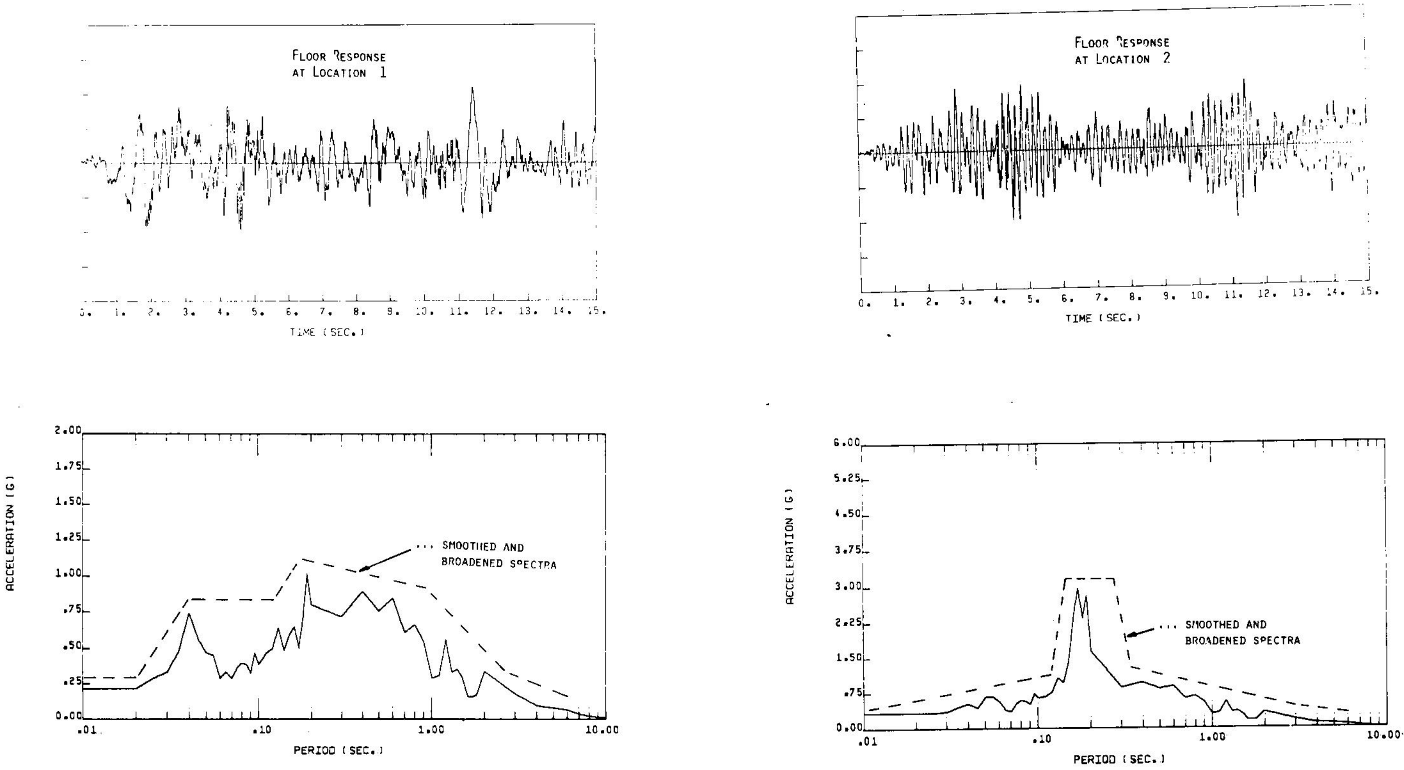

Fig. 2 Floor Response in a Typical Reactor Model

(a) Sine Sweep

(b) Continuous Sine

(c) Decaying Sine

(d) Sine Beat

Fig. 3 Single Frequency Test Motions

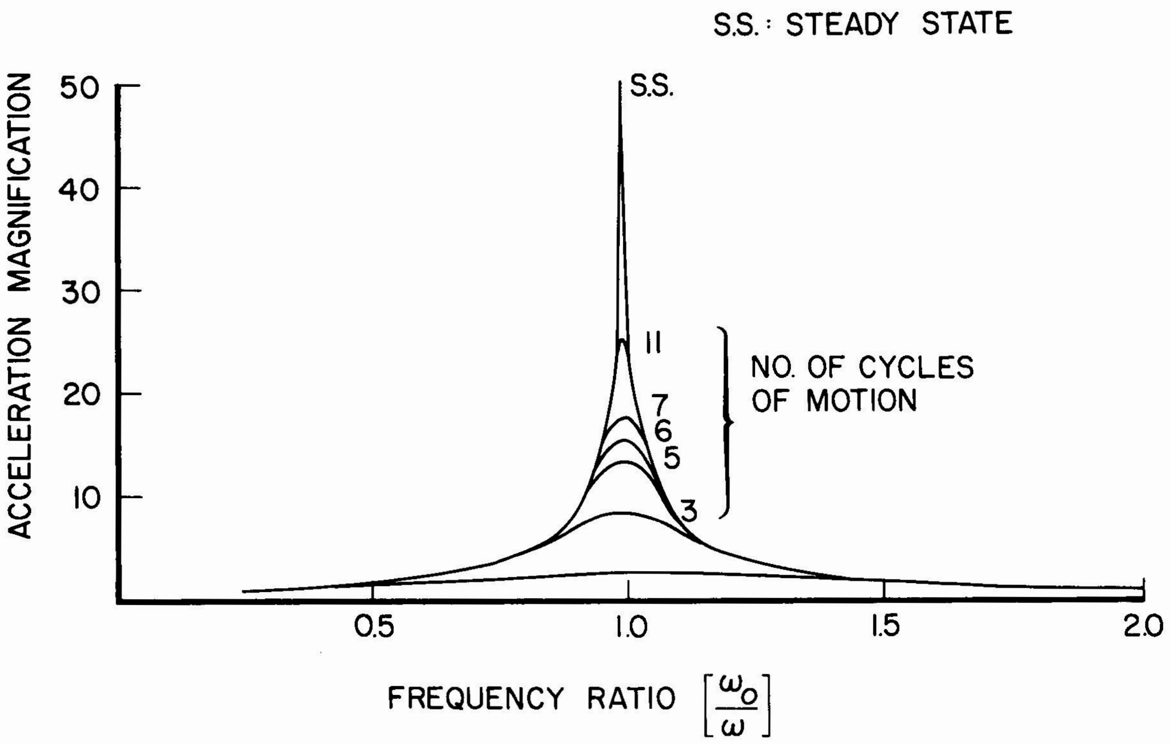

Fig. 4 Magnification of Acceleration for Sinusoidal Table Motion of Varying Duration

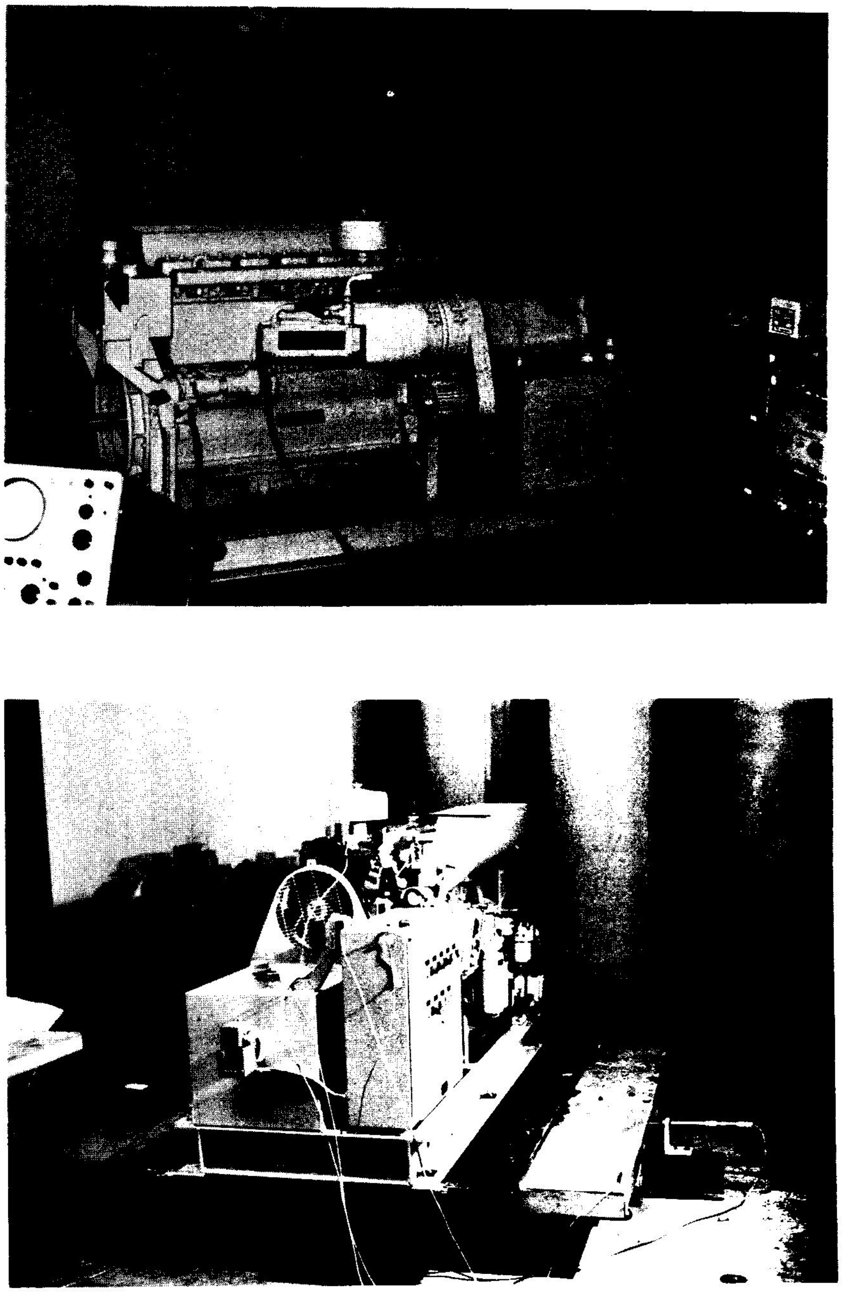

Fig. 5 Diesel Engine Mounted on Horizontal Shake Table

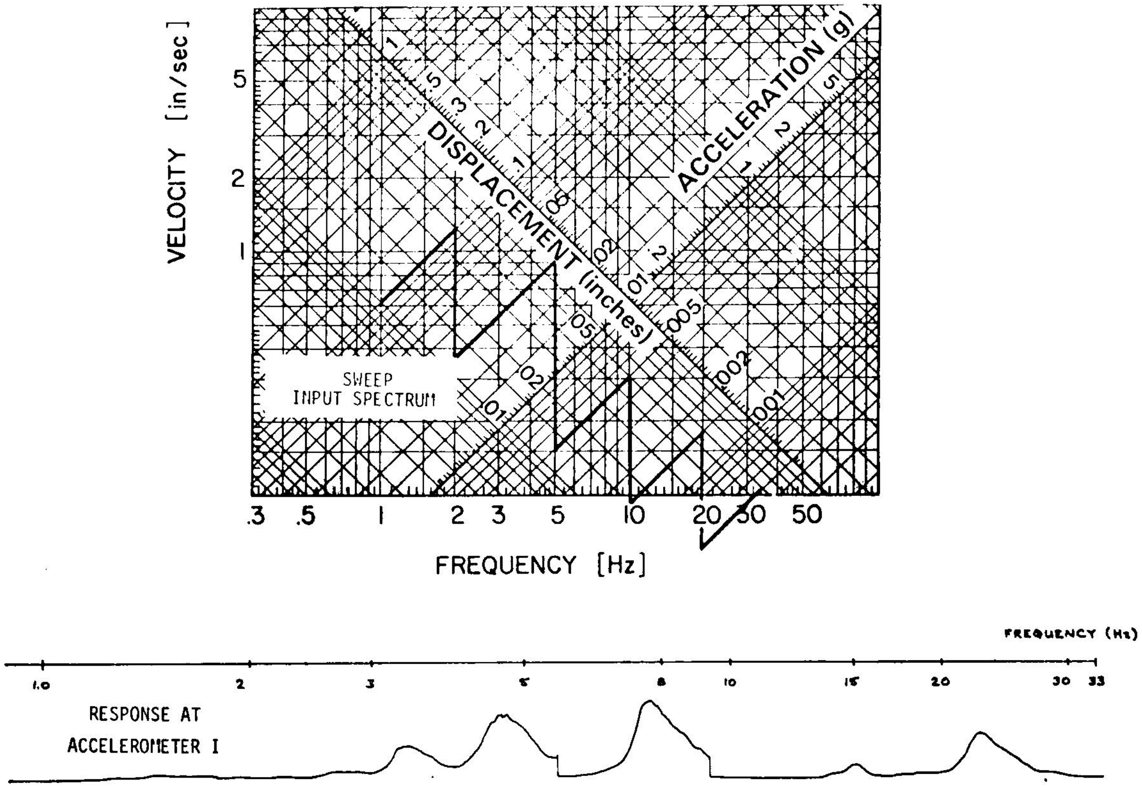

Fig. 6 Sweep Test on Diesel Engine

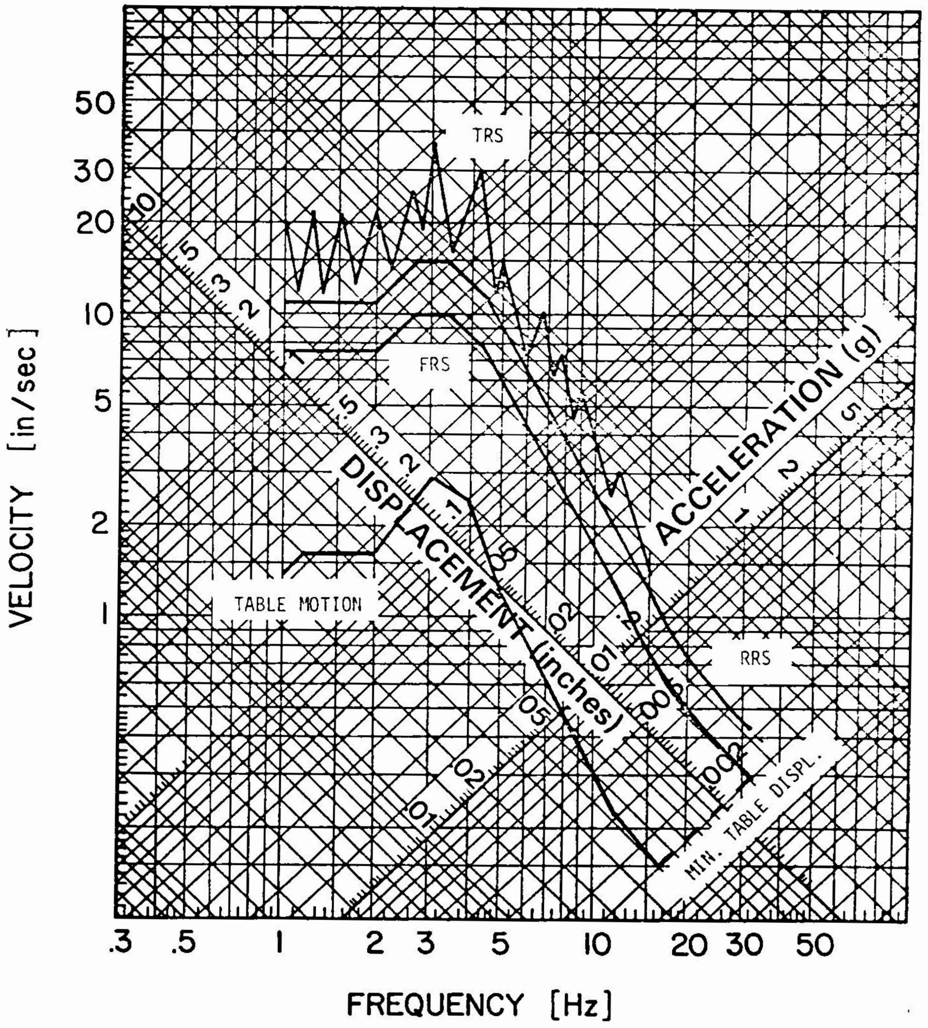

Fig. 7 Test Spectra