DEVELOPMENT AND USE OF SEISMIC INSTRUCTURE RESPONSE SPECTRA IN NUCLEAR PLANTS

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SUMMARY

This paper encompasses methods for the development of instructure response spectra as well as the use of these spectra in the seismic design and analysis of nuclear plant components.

The time history modal analysis, which is the most commonly used method to generate instructure response spectra in the United States, is described. This includes the effects of rigid body transformation associated with angular accelerations of the lumped mass nodal points due to eccentric locations of the equipment or system support points. When the locations of the support points are known, the instructure response spectra are simply generated at these points taking into account translational and angular accelerations in a straightforward manner as far as the formulation is concerned. On the other hand, when the locations of the support points are unknown, a general way of generating and using the instructure response spectra associated with both translational and angular input motions is presented. In this case the instructure response spectra due to translational excitations are used in conjunction with the ones due to rotational excitations.

Various numerical techniques for the integration of differential equations of motion are outlined. The time interval to be used in each method of numerical integration is chosen so as to avoid mathematical instability and inaccuracy. Comparison of the results using different techniques for the numerical integration of a sample problem, for the purpose of verifying solution accuracy, is provided.

Methods of developing instructure response spectra other than the time history method are discussed.

The use of three-dimensional instructure response spectra developed for each of the three orthogonal translational directions of ground motion is presented. Since the records show that earthquake motions occur in all three directions simultaneously, without consistent relations among them, the evaluation of the combined effects of these motions on equipment, systems and other components is described.

1. Introduction

Seismic response spectra of equipment support motion plays an important role in the seismic analysis, design and testing of the equipment of nuclear power plants. These response spectra, according to the present requirements by the regulatory agencies for reactor safety in the United States, are developed using an artificial time history of the free-field ground motion which matches the design smooth response spectra developed on the basis of actually recorded seismic accelerograms [1]. However, there are other simplified methods developed for the generation of instructure response spectra such as the one suggested by Biggs [2, 3, 10, 11], the one proposed by Kapur and Shao [4], and the one presented by Jankov and Reeves [5].

Earthquake ground motions are recorded in three orthogonal translational directions. However, for unsymmetrical arrangements of structures the equipment support motions within a structure can be excited by the ground motions in all directions associated with all six degrees of freedom, namely, three translations in the three orthogonal principal directions and three rotations about the three orthogonal principal axes. Very often in generating instructure response spectra the effects of motions of angular rotations at the equipment support point are neglected, which may be erroneous. Therefore, the generation and use of instructure response spectra with the effects of angular motions of the support points of equipment are presented here.

2. Generation of Equipment Support Motion Time History

In order to generate the time history of the equipment support motion, an artificial time history of the free-field ground motion has first to be developed [6, 7, 8]. According to the present requirements by the regulatory agency for nuclear safety in the United States, the artificial time history of the free-field ground motion should yield the spectra which lie above the smooth design response spectra at almost all period points [6, 8]. The smooth design ground response spectra, according to the present position of the regulatory agencies, should be developed as suggested by Newmark, Blume and Kapur [1].

Horizontal time history of the free-field ground motion developed [8] for a particular site of a nuclear power plant of the pressurized-water reactor (PWR) type is shown in Figure 1. Once the artificial ground motion is developed, the next step is to subject a mathematical model which consists of lumped masses, elastic properties and dashpots in discrete parts to this ground motion. Then the time histories at desired locations of the lumped-mass model are generated by the use of free vibration characteristics. The lumped-mass mathematical models are selected so that they properly represent dynamic behavior of the structures. For example, Figure 2d shows a lumped-mass model of an auxiliary building of a PWR plant. The masses, as can be seen in Figure 2b, are lumped at floor levels. Each mass is assumed to have six degrees of freedom, namely, three translations in the three orthogonal principal directions and three rotations about the three orthogonal principal axes. After the free vibration analysis of this lumped-mass mathematical model, the model was subjected to the ground motion, Figure 1, in the x direction according to the coordinate system shown in Figure 2c. Time-history motion of the roof, which is simulated by mass m_1 as shown in Figure 2b, in the x direction is then generated as shown in Figure 3. This was accomplished by the use of a digital computer program based on the formulation presented in Reference [6], which applies the numerical method of Simpson's rule for integration of decoupled modal differential equations of motion. The same time history, for verification purposes, was generated using a digital computer program based on fourth-order Runge-Kutta method [9], which is shown in Figure 4. Both time histories, for any practical purposes, are essentially the same.

When the location of the support point of uncoupled subsystems, that are located away from the centers of gravity of the lumped mass, is known, the time histories of the support motions at that point, in general associated with all six degrees of freedom, are generated for each direction of ground motion. These time histories of the support motions are used as inputs for the generation of instructure response spectra. The time history of the support point, in general, in any translational orthogonal direction is generated by the superposition of associated translational acceleration at the center of gravity of the lumped mass and the product of angular accelerations about the two axes perpendicular to the axis of the translational motion and the distances from the center of gravity of the lumped mass along the axes perpendicular to the axes of rotation and the translational motion. This is accomplished at any instant of time for the entire duration of the earthquake.

When the location of the support point of uncoupled subsystems cannot be readily determined with regard to which lumped mass it belongs, a straight line interpolation procedure may be used to solve the problem.

3. Development of Instructure Response Spectra

After the time dependent instructure support motions, in general associated with all six degrees of freedom due to each direction of ground motion, are generated, the next step would be to subject single oscillators with varying natural periods and damping factors of interest to these support motions. Then the maximum response acceleration of single oscillators are plotted versus their natural periods for each damping value desired. These plots represent the instructure response spectra which can be used in the spectrum analysis of uncoupled light subsystems. It should be noted that it is a conservative approach if the instructure response spectra are used for the analysis of uncoupled subsystems when their mass is not small compared to that of the supporting structure.

Figure 5 shows smoothed three-dimensional instructure response spectra developed for the motions of the outermost support of a steam generator at the operating floor in a PWR plant. These spectra are developed for the three translational orthogonal directions of the support motion for the condition of ground motion in the horizontal x direction (y being vertical axis), which includes the effects of angular accelerations of the lumped mass simulating the operating floor. This particular plant is founded on a firm rock with 9,000 ft/sec shear wave velocity so that the principal contribution to the response of this unsymmetrical structure is due solely to the flexibility of the superstructure since the effects of rock-structure interaction are entirely suppressed. This is reflected in the response spectra which consist of resonance peaks at the natrual frequencies of the superstructure. The upper bound envelopes of the peaks are used for the construction of the response spectra. The resonance peaks are widened by ± 10 percent of the resonance frequencies to account for the uncertainties associated with computed natural frequencies of the superstructure.

Three-dimensional response spectra due to translational and rotational motions of the top floor of the building shown in Figure 2 for the condition of ground motion in the z direction are shown in Figures 6 and 7, respectively. The shifting of the resonance peaks are due primarily to the uncertainties associated with the parameters of soil-structure interaction. Therefore, the unsmoothed response spectra associated with the upper and lower bound estimates of the soil-structure interaction parameters are superimposed and then enveloped as shown in Figures 6 and 7. Spectral accelerations of Figure 6 are due to the three orthogonal translational directions of motion of a certain point within the lumped mass simulating the floor with portions of shear walls. Coordinates of this point are according to the coordinate system shown in Figures 2a, 2b and 2c and are shown in Figure 6. The spectral accelerations are designated as a_i, where subscript i corresponds to the direction of the floor motion associated with the translational directions of the three orthogonal principal axes. Spectral accelerations shown in Figure 7 are due to rotational motions obtained as products of spectral angular accelerations and the lever arm $r = 100$ feet. These accelerations are designated as A_1, A_2 and A_3, where subscripts 1, 2 and 3 correspond to the floor rotational motions about the X, Y and Z axes, respectively.

Linear-acceleration method [12] is used for the numerical integration of differential equations of motion of single-degree-of-freedom systems for the development of response spectra shown in Figures 5, 6, 7 and 8.

4. Verification of Computation Accuracy

In order to verify the computed time history of the top floor of the building shown in Figure 2, two different numerical methods of integration are used. The time history of the top floor motion in the x direction shown in Figure 3 is generated using Simpson's rule for numerical integration of convolution integrals in equations for modal relative displacement, velocity and acceleration in terms of normal coordinates [6]. The integration time interval used is 0.01 seconds. The same time interval is used for plotting. The solution procedure is based upon the step-by-step method. The modal relative displacement and velocity from the previous step are used as initial conditions for the next step. At each step the modal relative displacement, velocity and acceleration are calculated. The absolute acceleration is then obtained by modal superposition. The time history shown in Figure 4 is generated by the use of a computer program based on fourth-order Runge-Kutta method with variable integration interval [9] for direct integration of decoupled second order modal differential equations of motion expressed in normal coordinates. This computer program uses Sompson's rule for error estimation. The input integration time step is 0.002 seconds. The output has been digitized at 0.01 and 0.005 second time intervals and the results due to both intervals are essentially the same. However, the computer plot shown in Figure 4 is based on the 0.01 second time interval. Comparing time histories of Figures 3 and 4 it can be concluded that they are both well in agreement.

The response spectrum shown in Figure 8 is developed by subjecting single-degree-of-freedom systems with varying natural periods and 1 percent damping factor to the time-history motion shown in Figure 3. The integration time step used is 0.01 seconds. The period intervals are 0.025 seconds in the short period range between 0 and 0.1 seconds, 0.015 seconds in the period range between 0.1 and 0.7 seconds, and 0.05 seconds in the long period range with particular consideration given to resonance peak at the structure dominant frequency. The response spectrum shown in Figure 9 is developed for 1 percent of equipment critical damping using as input the time history shown in Figure 4. Fourth-order Runge-Kutta method with variable integration time interval in conjunction with Simpson's rule for error estimation is used [9]. The input integration time interval used is 0.002 seconds. The period interval used is 0.0125 seconds. Response spectra shown in Figures 8 and 9 are, for any practical purposes, essentially in agreement, except at the resonance peak. Further investigation, with a smaller period interval of 0.00625 seconds in the resonance range, shows that the resonance peak of Figure 9 is the more appropriate one.

5. Use of Response Spectra

When the response spectrum concept of analysis is used, only the maximum modal responses are known, and the phasing of modes cannot be determined as in time-history analysis. The total response of a point in the multi-degree-of-freedom system can, therefore, only be approximated. The maximum responses are normally taken to be the square root of the sum of the squares of maximum modal responses. For closely spaced modal frequencies, the maximum modal responses are normally combined on the absolute sum basis.

The proper way of using the spectra associated with all six degrees of freedom at the support point of equipment for each direction of the free-field ground motion is to compute the maximum responses of the equipment resulting from these spectra. Then the maximum responses associated with all three orthogonal directions of the ground motions are combined by the square root of the sum of the squares of these responses.

A conservative approach of using the spectra associated with all six degrees of freedom for each direction of ground motion would be to combine spectra on the square root of the sum of the square basis. If the principal contribution to the response of the support point associated with coupled translational and rotational motions are due to closely spaced modal frequencies of the supporting structure, the spectral accelerations may be conservatively combined as absolute values.

When the equipment support point cannot be readily determined as to which lumped mass it belongs, a straight line interpolation may be used.

The significance of spectral angular accelerations of a support point upon the design and analysis of equipment depends on the idiosyncracy of the design of the supporting structure and on the properties of the foundation material.

When spectrum analysis is used for systems or components with different support motions such as piping systems, cable trays, electrical bus ducts and other components, the instructure response spectra for all support points should be superimposed for a given component of motion.

6. Other Methods for Generation of Instructure Response Spectra

Besides the most commonly used method based upon time-history analysis for generating instructure response spectra, there are other methods such as the one developed by Biggs [2, 3, 10, 11], the one suggested by Kapur and Shao [4], and the one proposed by Jankov and Reeves [5]. The latter methods are the short-cut procedures for developing instructure response spectra. Although the method based upon time-history analysis has been automated, it is still a costly and time-consuming process. The only method, however, acceptable, at the present time, to the regulatory agencies for reactor safety in the United States is the one based upon time-history analysis.

The short-cut procedures are based upon the results of a response spectrum analysis of the supporting structure and make use of the amplification factors for generating instructure response spectra.

One of the shortcomings of the short-cut methods for generating the instructure response spectra is that the methods yield much too conservative results in the short period range for resonance conditions. Hence, these methods need further improvements. For example, the peaks of the amplification curves may be treated as frequency dependent so that the peaks of amplification curves approach unity as the structure and equipment frequencies approach absolute rigidity range.

Comparison of the results of resonance peaks due to the crane support motion of a boiling-water reactor (BWR) building using different methods are shown in Table I. There are substantial differences in the results.

The differences in the results using time-history, Biggs and Kapur-Shao methods are due primarily to the different time histories used; i.e., the ground motion used in the time-history method is different from the ones used for generating the amplification factors in the Biggs and Kapur-Shao methods. Therefore, the question arises as to what time history of the ground motion is to be used, even in the time-history analysis, since there is more than one time history of the ground motion compatible with the ground response spectra. Each of these time histories can yield radically different peaks of instructure response spectra. Hence, there is obviously a great deal of uncertainty as to what time history of the ground motion is to be used as input.

Acknowledgement

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Table I. Comparison of resonance peaks due to crane support motion of a (BWR) steel containment using different methods for generating instructure response spectra.

Natural Frequency Hz	Resonance Peak Accelerations in g's for Equipment Damping of 2 percent of Critical Damping		
	Time-History Method	Biggs Method	Kapur-Shao Method
3.60	4.30	1.62	2.84
5.40	2.81	2.85	3.53
10.70	3.32	2.60	4.33

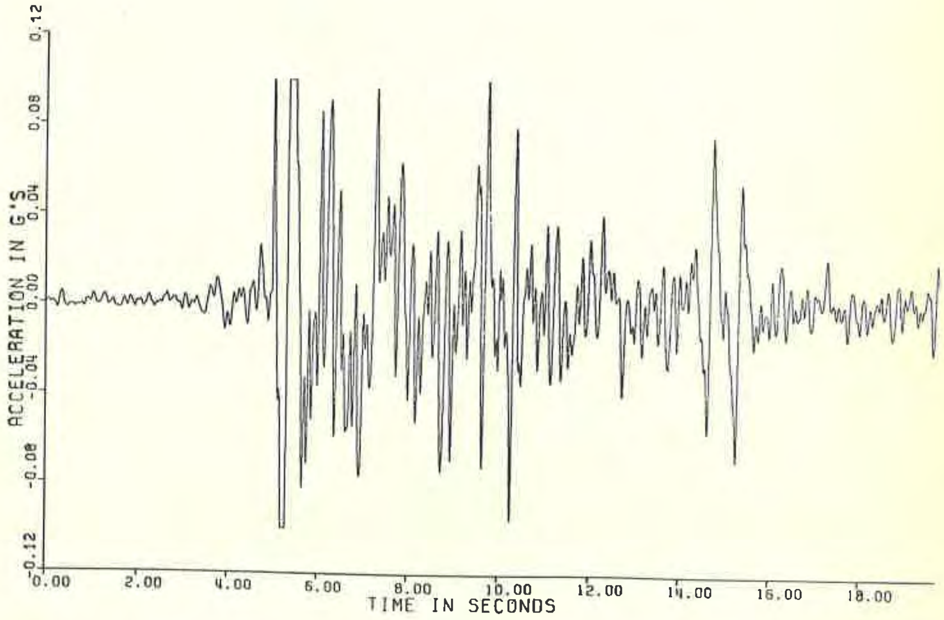
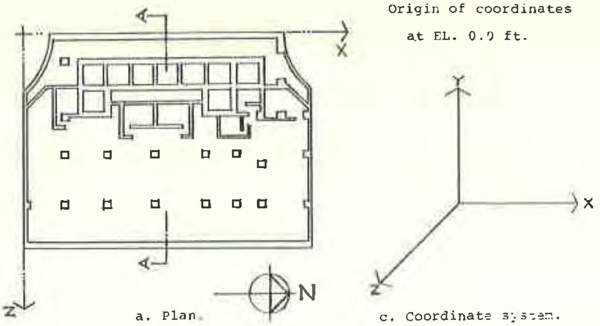
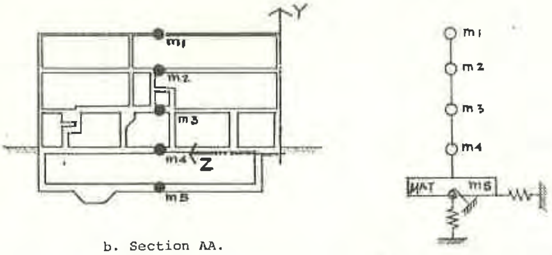


Figure 1. An artificial time history of the free-field ground motion.



a. Plan.

c. Coordinate system.



b. Section AA.

d. Mathematical model.

Figure 2. An auxiliary building in a PWR plant.

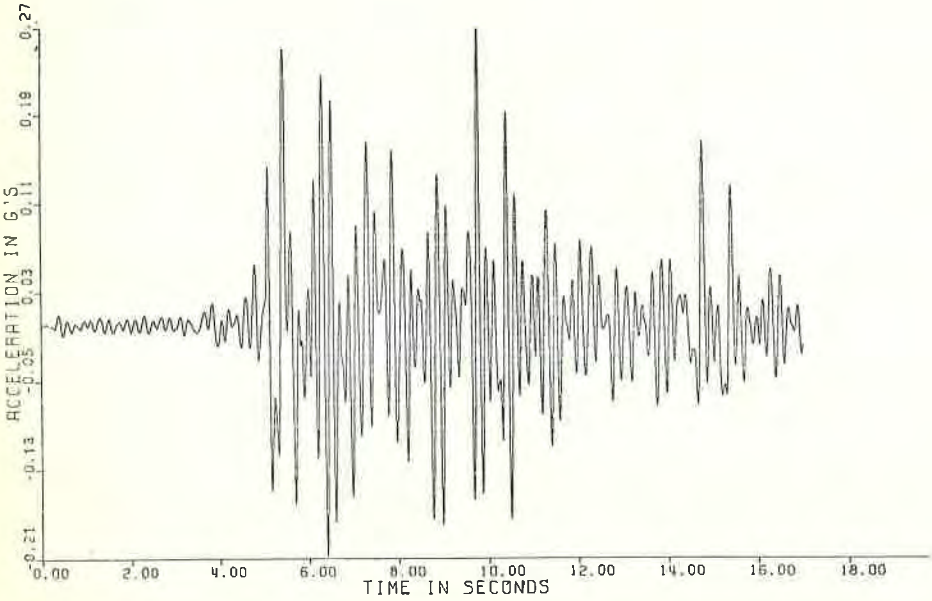


Figure 3. Time history of the horizontal motion in the x direction of the top floor of the building shown in Figure 2 generated by the use of Simpson's rule for numerical integration.

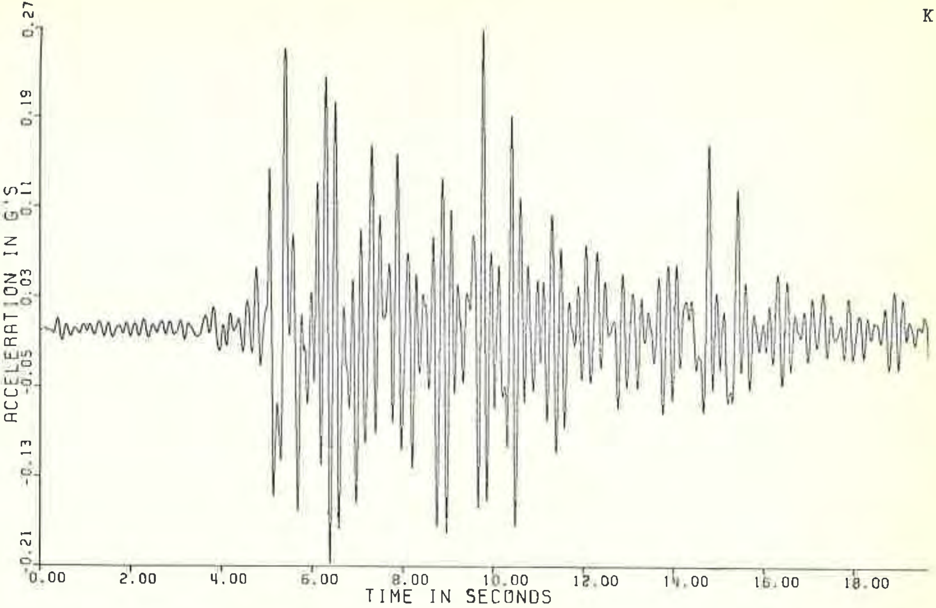


Figure 4. Time history of the horizontal motion in the x direction of the top floor of the building shown in Figure 2 generated by the use of Runge-Kutta method for numerical integration.

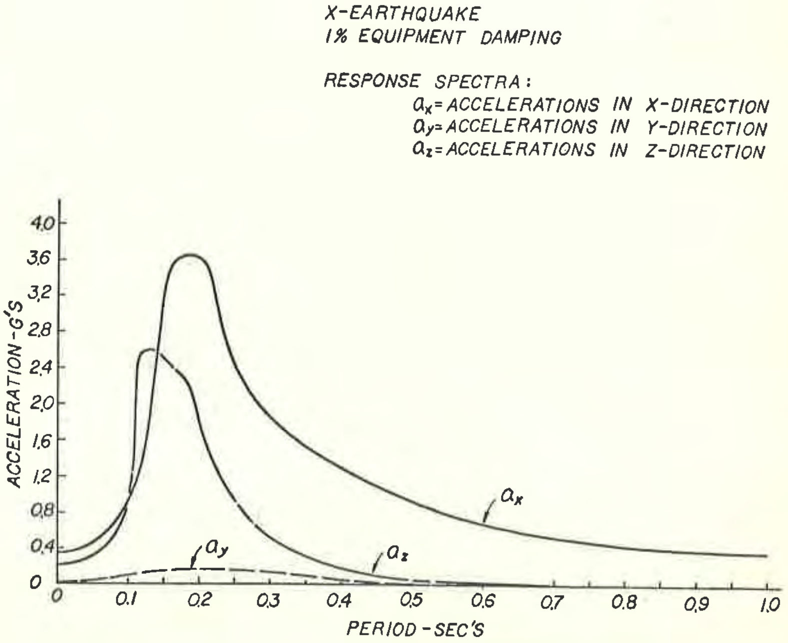
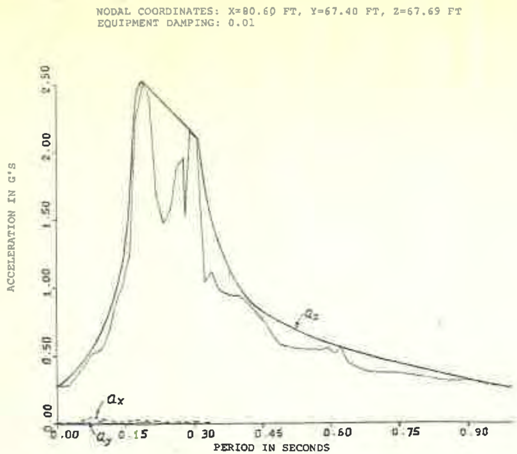
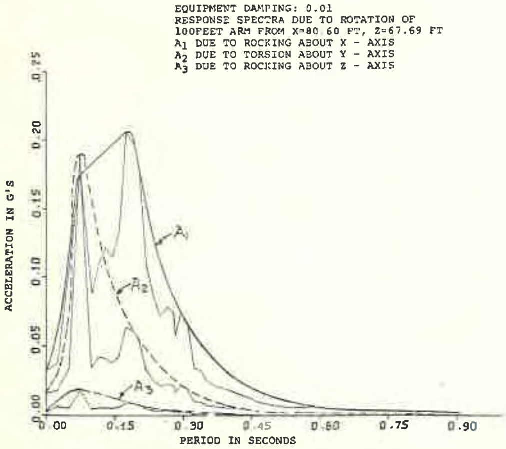


Figure 5. Three-dimensional smoothed response spectra at the outermost steam generator support of a PWR plant.



NODAL COORDINATES: X=80.60 FT, Y=67.40 FT, Z=67.69 FT
EQUIPMENT DAMPING: 0.01

Figure 6. Three-dimensional response spectra due to translational motions of the top floor of the building shown in Figure 2 for the condition of ground excitation in the z direction.



EQUIPMENT DAMPING: 0.01
RESPONSE SPECTRA DUE TO ROTATION OF
100FEET ARM FROM X=80.60 FT, Z=67.69 FT
A_1 DUE TO ROCKING ABOUT X - AXIS
A_2 DUE TO TORSION ABOUT Y - AXIS
A_3 DUE TO ROCKING ABOUT Z - AXIS

Figure 7. Three-dimensional response spectra due to rotational motions of the top floor of the building shown in Figure 2 for the condition of ground excitation in the z direction.

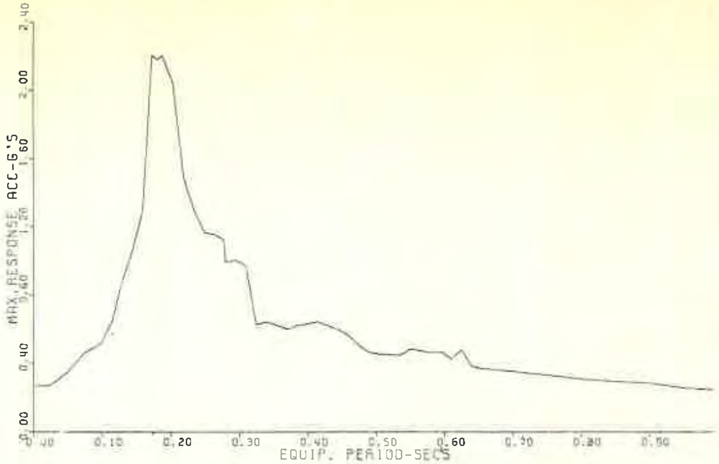


Figure 8. Response spectrum due to the time history of Figure 3.

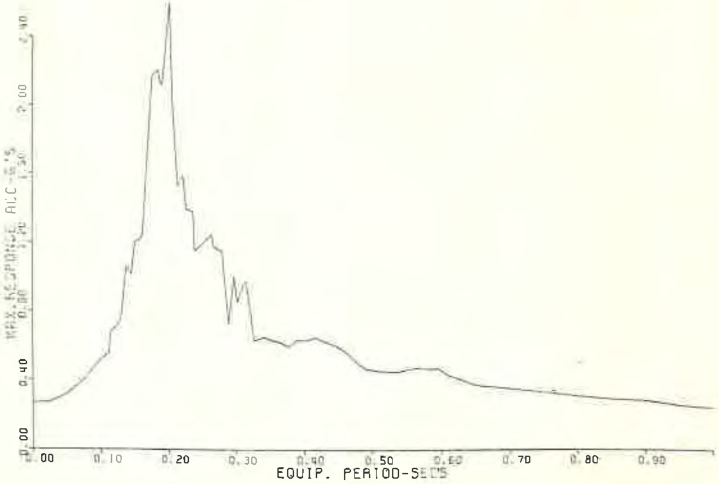


Figure 9. Response spectrum due to the time history of Figure 4.