BNL-66292
Informal Report

IMPLEMENTATION OF SEISMIC STOPS

IN PIPING SYSTEMS

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February 1993

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Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Contract No. DE-AC02-98CH10886

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ABSTRACT

Commonwealth Edison has submitted a request to NRC to replace the snubbers in the Reactor Coolant Bypass Line of Byron Station -Unit 2 with gapped pipe supports. The specific supports intended for use are commercial units designated "Seismic Stops" manufactured by Robert L. Cloud Associates, Inc. (RLCA). These devices have the physical appearance of snubbers and are essentially spring supports incorporating clearance gaps sized for the Byron Station application. Although the devices have a nonlinear stiffness characteristic, their design adequacy is demonstrated through the use of a proprietary linear elastic piping analysis code "GAPPIPE" developed by RLCA. The code essentially has all the capabilities of a conventional piping analysis code while including an equivalent linearization technique to process the nonlinear spring elements.

Brookhaven National Laboratory (BNL) has assisted the NRC staff in its evaluation of the RLCA implementation of the equivalent linearization technique and the GAPPIPE code. Towards this end, BNL performed a detailed review of the theoretical basis for the method, an independent evaluation of the Byron piping using the nonlinear time history capability of the ANSYS computer code and, by result comparisons to the RLCA developed results, an assessment of the adequacy of the response estimates developed with GAPPIPE. Associated studies included efforts to verify the ANSYS analysis results and the development of bounding calculations for the Byron Piping using linear response spectrum methods.

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EXECUTIVE SUMMARY

A request to allow the replacement of snubbers in the Reactor Coolant Bypass Line of Byron Station - Unit 2 with commercially produced gapped pipe supports was submitted to NRC. The commercial gapped pipe supports are designated "Seismic Stops" and are manufactured by Robert L. Cloud Associates, Inc. (RLCA). A description of the evaluations performed by Brookhaven National Laboratory (BNL) to assist the NRC staff to respond to this request is presented.

Gapped pipe supports can reduce piping vibrations by limiting the amplitude of free vibrations. The Seismic Stops incorporate engineered gaps in mechanical devices to meet this purpose. Although these devices exhibit nonlinear characteristics, RLCA has developed a proprietary linear elastic piping analysis code, "GAPPIPE," to demonstrate the design adequacy of the devices in piping systems. BNL performed a detailed review of the theoretical basis for GAPPIPE code and independent evaluations of the response of the Byron Piping with gapped supports using nonlinear time history analyses and bounding linear response spectrum analyses.

Based on the evaluations, it was concluded that properly designed gapped supports could effectively control seismic motions. The GAPPIPE code was determined to provide estimates of piping system response with an accuracy consistent with the response spectrum methodology. Further, in general, the code can be expected to provide conservative estimates of the time averaged support forces.

1. INTRODUCTION

The redesign and optimization of piping support systems has received considerable attention in recent years. A primary aim of these redesign efforts is to reduce the number of snubbers used in the support system. Snubber reduction is desirable since it directly reduces the time consuming and costly inspection and maintenance operations required for snubbers and the likelihood of adverse system response associated with snubber malfunctions. Such redesign efforts are referred to as snubber reduction programs.

One approach to snubber reduction is to simply replace each snubber with an alternate support device. To be comparable to a snubber such a device must accommodate thermal expansions while restricting excessive seismic motions. A passive device which has these characteristics is a gapped pipe support. Ideally the gap is large enough to allow free thermal expansion while small enough to limit seismic motions to acceptable levels.

Gapped supports made up of box frames surrounding the pipe but with a clearance gap around the entire circumference are used in fossil fuel power plants. Commercial units, designated "Seismic Stops," incorporating clearance gaps sized for specific applications, are manufactured by Robert L. Cloud Associates, Inc. (RLCA) for use in the nuclear industry. These devices have the physical appearance of a snubber (Figure 1), and are designed to allow pin to pin snubber replacement.

The adequacy of nuclear piping systems and their associated supports are typically demonstrated using linear elastic analysis methods. The gapped support, however, is a non-linear element and its inclusion in a system poses computational complexities. In order to market the seismic stop, RLCA has developed a proprietary linear-elastic piping analysis code which uses equivalent linearized properties to simulate these restraints. The RLCA code is titled "GAPPIPE" and essentially has all the computational capabilities of a conventional piping analysis code while including the equivalent linearization option.

Commonwealth Edison (CE) has submitted a request to replace the snubbers in the Byron/Braidwood units with seismic stops. The actual calculations to determine the required sizes and number of restraints was performed by RLCA using the GAPPIPE code. Brookhaven National Laboratory (BNL) has assisted the staff in its evaluation of the RLCA linearization methodology and the application of the methodology to the analysis of the Byron/Braidwood piping systems with seismic stops. Specifically, BNL performed a detailed review of the theoretical basis for the methodology, a review of the implementation of the methodology in the GAPPIPE code, an independent evaluation of the Byron/Braidwood piping using the non-linear time history capability of the computer program ANSYS, a study to verify the non-linear capability of the ANSYS code and bounding calculations for the Byron/Braidwood piping using the linear response spectrum option of the ANSYS code.

The sections that follow provide a description and summary of the BNL studies.

2. GAPPIPE METHODOLOGY DESCRIPTION

The GAPPIPE computer program is a full featured, finite element piping analysis, code. It was developed by RLCA by expanding and modifying the public domain structural analysis code SAPIV. A key feature of the code is the incorporation of an analysis algorithm designed specifically to allow the dynamic evaluation of piping systems with gapped supports using linear elastic response spectrum methods. The methodology is called equivalent linearization analysis.

In the method each gapped support or seismic stop in the mathematical model of the piping systems is replaced with an equivalent linear spring. The stiffness of the equivalent linear spring is determined by minimizing the mean difference of the support restoring force between each equivalent spring and the corresponding gapped spring. The mean difference is an average over time across the response duration and is derived based on random vibration concepts. A summary of the detailed formulations of the method as implemented in GAPPIPE is provided in the User's manual for the code and is presented in the following.

Figure 2 shows the force-displacement relationship of a symmetric gapped support. The gapped support has a stiffness equal to K_g after the gap is closed. Let g be the gap size; F be the support force as a function of the pipe displacement, x, in the direction of the support; K_{LIN} be the equivalent linearized stiffness to be determined by a minimization process. The following equation defines the difference, D, between the restoring forces of the gapped support and its equivalent linearized spring at any instance of time, t as

$$D(x(t)) = F(x(t)) - K_{LIN}x(t) \qquad (1)$$

where

$$F(x) = \begin{cases} 0 & when\ |x| < g \\ K_g(x(t) - g) & when\ |x| > g \end{cases} \qquad (2)$$

and | | denotes that the absolute values of x be used.

For the case where the system is exhibiting quasi harmonic response the pipe displacement may be expressed as:

$$x(t) = A(t)\cos\theta \qquad (3)$$

where
$\theta = \omega t - \phi(t)$

and ϕ is the phase angle.

In the above, although the amplitude and phase angle are time dependent, they vary slowly with time and are assumed to be constant over a cycle.

The equivalent linearized stiffness is determined by minimizing the mean value of the square of the force difference, Eq. (1) over a cycle. The mean square of the difference, D_m over a cycle of vibration may be expressed as:

$$D_m = \frac{1}{T}\int_0^T (D(x(t)))^2 dt \qquad (4)$$

where $T = 2\pi/\omega$

and the minimization requires:

$$\frac{d\,D_m}{d\,k_1} = 0 \qquad (5)$$

where k_1 is the linearized stiffness corresponding to quasi harmonic response and can be seen as a constant over each cycle.

Using relations 1 and 4 Equation 5 provides:

$$\frac{1}{T}\int_0^T [-2xF(x) + 2k_1x^2]\ dt = 0 \qquad (6)$$

Incorporating relation (3), and realizing that if $\phi(t)$=constant, $d\theta/dt=\omega$, provides:

$$\int_0^{2\pi} [- A\ Cos\theta\ F(x) + k_1A^2\cos^2\theta\ ]d\theta = 0 \qquad (7)$$

which yields:

$$k_1(A) = \frac{1}{\pi A}\int_0^{2\pi} F(x)\ \cos\theta\ d\theta \qquad (8)$$

for the equivalent linearized stiffness associated with quasi harmonic response.

During a seismic event, the pipe response is not harmonic. Thus, due to the randomness in displacement amplitudes in dynamic response, the minimization of the mean squared difference needs to be performed using the methods of random vibration. The minimization process is, therefore, applied to the expectation of the mean square difference rather than to the mean square itself.

Although the pipe response is not harmonic over the duration of the seismic event it can be assumed to be quasi harmonic over each cycle in the response and to have a different amplitude magnitude associated with each cycle. The response then would exhibit a spectrum of displacement amplitudes and frequencies.

The expected value of the mean squared difference can be expressed as:

$$E[D_m] = \lim_{T\to\infty} \frac{1}{T}\int_0^T D_m \, dt \tag{9}$$

and minimizing this quantity with respect to the weighted average of the equivalent linearized spring, K_{LIN}, over the time duration requires:

$$\frac{d\, E[D_m]}{d\, K_{LIN}} = 0 \tag{10}$$

If it is assumed that the response is a stationary, narrow banded process, K_{LIN} can be determined using the value of D_m given by equation 4. Using Equation 4 and replacing k_1 with K_{LIN} provides after differentiation with respect to K_{LIN}.

$$\frac{d\, E[D_m]}{dK_{LIN}} = \lim_{T*\to\infty} \frac{1}{T*} \int_0^{T^*} [\frac{1}{T} \int_0^T (-2x(t)F(x)$$

(11)

$$+2K_{LIN}\, x^2(t))dt]dt^* = 0$$

Using equation 8 both expressions in this equation can be expressed in terms of the amplitude dependent equivalent linear spring constant for one cycle k_1(A) and the amplitude A, providing:

$$\lim_{T^*\to\infty} \frac{1}{T^*}\int_0^{T^*}[-\frac{1}{\omega}k_1 \; \pi \; A^2 + K_{LIN}\, A^2]dt^* = 0$$

(12)

Solving for K_{LIN} yields:

$$K_{LIN} = \frac{\lim_{T\to\infty}\frac{1}{T}\int_0^T k_1 A^2 dt}{\lim_{T\to\infty}\frac{1}{T}\int_0^T A^2 dt} \tag{13}$$

or written in terms of the expectation operator

$$K_{LIN} = \frac{E\,[A^2\, k_1]}{E\,[A^2]} \tag{14}$$

Essentially this states that K_{LIN} is the weighted average of k_1(A) over all amplitudes A.

The calculation of K_{LIN} is carried out by numerical means in an iterative manner until convergence in accordance with an acceptance criteria is achieved. In general, the procedure begins assuming that all linearized stiffnesses are zero as if the gapped seismic stops are not present. The pipe displacement responses at gap location are then calculated using the conventional reponse spectrum method. Based on these responses, a new set of linearized stiffnesses are calculated using the linearization procedure described above. With this new set of linearized stiffnesses added to the piping system, the response spectrum analysis procedure repeats. The iteration continues until the changes in the linearized stiffnesses for all gaps are within prescribed tolerances.

This procedure is outlined step-by-step in the following:

(1) Assume a null [K_{LIN}].
(2) Add [K_{LIN}] to [K].
(3) Perform the response spectrum analysis to determine the maximum displacement amplitudes at gaps.

(4) Use the maximum displacement amplitudes to calculate a new $[K_{LIN}]$.

(5) Compare the old and new $[K_{LIN}]$'s to see if the difference is within the prescribed tolerance for every gap. If all differences are within the tolerances, the solution is converged.

(6) If the tolerance is exceeded by at least one gap, a new updated $[K_{LIN}]$ is calculated for use in the next iteration using the following formula:

$$[K_{LIN}\ \text{Updated}] = (1\text{-}b)[K_{LIN\ OLD}] + b[K_{LIN\ NEW}]$$

where b is a convergence factor, $b \leq 1$

(7) Go to step (2) and process repeats.

The whole solution process is a repetition of the response spectrum analysis procedure. The nonlinearity is embedded in the linearization procedure and the interaction between gapped supports is inherently accounted for through the iterative solution.

3. METHOD AND IMPLEMENTATION REVIEW

As the first phase of the evaluation a review was made of the literature for the equivalent linearization method. It was found that the method had clearly been investigated by many authors (1-5). Of particular interest were the papers by W.D. Iwan (5-7) of CALTECH. He advanced applications of the method to estimate the seismic response of systems supported by nonlinear elements using response spectrum methods. The method as implemented in GAPPIPE (8-10) closely paralleled the procedures advanced by W.D. Iwan. Based on the review, it was concluded that there was a theoretical basis for the method, it could provide acceptable approximations of system response and its basic implementation in GAPPIPE followed the procedures recommended by a recognized researcher in the field.

Although the opinion of the method was essentially positive, several questions regarding its application to piping systems were raised. These were formulated and transmitted through the project monitor to RLCA. The BNL concerns were:

(a) will the iterative solution process remain stable when a large number of gapped supports exist in the system,

(b) conversely, is there a limit to how many gapped supports can be in a system,

(c) what is the sensitivity of the solution mode to the chosen acceptance tolerance and,

(d) if appropriate, would the solution predict or allow supports to remain open.

Following the literature review a visit was made to the RLCA offices in Berkeley, California. A thorough review of the development and current status of the GAPPIPE code and the seismic stop concept took place. In the course of the meeting detailed information dealing with the design concept of the RLCA seismic stop and its impact on the nuclear industry, its mathematical foundation and its implementation into the GAPPIPE code were discussed. In addition, information on physical tests conducted with piping systems incorporating seismic stops was provided. These included results of the HDR-SHAG, HDR-SHAM, and RLCA/EPRI tests. A full listing of the information provided is presented in Appendix A.

Discussions and the information provided during the visit brought a resolution to each of the BNL concerns. Examples demonstrating that stable solutions were achieved for systems incorporating numbers of seismic stops of engineering interest were provided.

Figure 3 illustrates one such example. It shows how the predicted or estimated value of the linearized spring constant (K_{Lin}) and the resultant calculated value of the linearized spring constant converge to a value within the convergence tolerance. The illustration corresponds to the convergence of one gapped element in a piping system, Figure 4, incorporating 16 gapped elements. Each cycle corresponds to making an estimate of K_{Lin} from the prior results (shown by □ symbol) and calculating K_{Lin} corresponding to this estimate based on a response spectrum solution for the entire piping system (shown as a + symbol). For the example shown, more than 50 iterations were required to establish K_{Lin} for the specific element, and iterations would proceed until convergence within tolerance for all gapped elements was achieved.

In the examples, instances where the converged solution corresponded to the condition that a gap remained open were shown. As a practical matter, in such cases, the support would be removed from the final design as its inclusion in the system offered no benefit.

The complexity of the interaction is related to the number of gapped supports in the system. It has been observed that the number of iterations to achieve convergence is proportional to this number and computational time increases accordingly. Regarding the convergence criterion, a tolerance of 10% of the linearized stiffness is used. This criterion appears to provide estimates of piping system response with an accuracy consistent with that associated with response spectrum methods.

The physical tests for which results were provided were carried out over the years under the sponsorship of RLCA and EPRI. They were conducted to investigate seismic stop performance, demonstrate their capacity to control vibrations and to allow a comparison of their performance to other seismic motion restraining mechanisms. For most tests computations using the GAPPIPE code were made to demonstrate the adequacy of its response predictions.

In the 1988 RLCA/EPRI tests the seismic response of a piping system supported and excited by a multi-story frame was investigated. Two sequences of tests were conducted. In one, the piping was restrained by snubbers and supports, in the other it was restrained by seismic stops and supports. The measured responses demonstrate that seismic stops provide as much control of system response as do snubbers.

In the HDR-SHAG and HDR-SHAM tests a piping system in the shutdown HDR nuclear plant was subjected to operating level and high level simulated seismic excitations. In each test series alternate support systems were used in a sequential fashion to support and restrain the piping. The support systems included a flexible (soft) system, a rigid (stiff) system incorporating snubbers, a system using energy absorbers in place of snubbers and a system using seismic stops instead of snubbers. For all tests corresponding analytical estimates of system response were developed. The test results again demonstrated that the seismic stops control system vibrations as well as other support elements. The post test analytical results demonstrated that the estimates of system response developed with GAPPIPE were as accurate as the estimates of system response developed for the other systems using conventional analysis methods.

It was concluded after this review that the seismic stop represented an acceptable alternative to conventional restraint devices, that the equivalent linearization methodology was solidly based and its implementation by RLCA in the GAPPIPE computer code appeared theoretically correct and competently performed.

4. VERIFICATION ANALYSES

From the outset of the evaluation effort it was intended that the performance of independent analyses to confirm the adequacy of the seismic stops in the proposed application would be a major element of the evaluation. Further, it was also intended that the independent verification be performed using the non-linear time history capability of the computer program ANSYS. Using a recognized computer code in this application, it was thought, would enhance the credibility of the verification analysis results and preclude their discreditation if they were unfavorable.

The problem selected for the verification study was the Reactor Coolant Bypass Line for Byron Station-Unit 2. This is the exact line for which Commonwealth Edison requested approval for the application of seismic stops. A sketch depicting the system and showing key nodal points in the finite element model for the system is shown in Figure 5.

The system consists of 8 inch, 1 1/2 inch, and 3/4 inch SCH 160 type 304 stainless steel piping. System pressure is 2425 psi while system temperatures range from 120°F to 618°F with the majority of the piping being at a temperature 558°F. The system includes one relief valve, three check valves and four stop valves. The system terminates at five anchor points and is supported by five rod hangers. The support system includes eight seismic stops, replacing thirteen snubbers, to provide seismic restraint.

The finite element model consists of 294 nodes and 379 elements. The 8 inch pipe extends from node 203 to 238, the 1 1/2 inch pipe from node 72 through node 180 to node 212 and the 3/4 inch pipe, in two segments, from node 7 to node 180 and from node 1 to node 115. Anchors exist at nodes 1, 7, 72, 203, and 238 while vertical support is provided at nodes 49, 102, 117, 162, and 171. The eight seismic stops are located at nodes 39, 44, 55, 98, 147, 151, 157, and 170. The stops at nodes 55, 98, and 170 provide restraint in the Z coordinate direction, the one at 151 in the Y direction, those at 39, 147 and 157 in the X and Z directions, and the one at 44 in the X and Y directions. A summary of model parameters are presented in Table 1.

All key parameters of the finite model were selected to be identical to those used by RLCA in their qualification calculations for this system. Towards this end BNL requested, and RLCA did provide, a complete description of the finite element model used in their evaluations. The GAPPIPE input file listing (SAP V format) for the dead weight analysis for the system satisfied this request. The parameters extracted from this listing included geometry, piping temperature, pressure, section properties and weight, valve section properties and weight, support stiffness, orientation and gap characteristics.

To proof test the BNL model both a dead weight and natural frequency run were made. Table 2 provides a comparative listing of the natural frequencies for the system. As can be seen, there is excellent agreement for the thirty natural frequencies computed. Although not shown, the level of agreement between the BNL and RLCA estimates of displacements for the dead weight loading was also excellent. These results substantiated that the ANSYS model was an equivalent to the GAPPIPE model.

In the frequency determination above, springs having location and orientation identical to the seismic stops were included in the model. These springs were assigned stiffnesses equal to the estimates of linearized stiffness predicted by GAPPIPE. Given this, the model test also assured that the location and orientation of the seismic stops were correct. For the non-linear time history analysis with ANSYS these locations and orientations were retained but the true gap and stiffness properties of the seismic stops were modeled. A listing of the seismic stop parameters including the GAPPIPE estimate of the equivalent linearized stiffness is presented in Table 3.

The next phase of the evaluation was to define the time history forcing function. The evaluations performed with GAPPIPE were envelope response spectrum evaluations based on N-411 damping and SSE input levels. As such, the loading was defined by three envelope acceleration spectra for the three coordinate directions, Figure 6. For the ANSYS analysis time history definitions of the system accelerations were required. Accordingly, a request was made to RLCA for the time histories corresponding to the SSE spectra. Unfortunately, BNL was advised that the desired time histories were not available.

To accommodate the analysis needs synthetic time histories consistent with the SSE response spectra were developed. This was accomplished using a modified version of the CARES computer code. The code was modified specifically for this evaluation to allow it to accommodate the N-411 definition of damping inherent in the design spectra. The resultant support SSE acceleration time history records for the three coordinate directions are shown in Figures 7, 8, and 9. As will be noted each record is 15 seconds long and the peak acceleration levels are 1.01, 0.98 and 0.78 for the X, Y, and Z directions respectively.

Three checks of the adequacy of the time history records were performed. These included a comparison of the spectra derived from the time history records with the target (Byron SSE) spectra, a determination of the power spectral density (PSD) curves for the time histories and a determination of the degree of correlation that exists between the time histories.

The comparison of spectra derived from the time histories (the generated spectrum) and the design spectra are shown in Figures 10, 11, and 12. As can be seen, the level of agreement is good with the generated spectra exceeding the design spectra to only a nominal amount. The PSD curves corresponding to the time histories are shown in Figures 13, 14, and 15. As can be seen, there is content throughout the frequency range. Finally, the correlation calculation indicated the correlation coefficient between X-Y as 0.04, between Y-Z as 0.03 and between X-Z as 0.003. In summary, the time histories were found to be uncorrelated, to have acceptable PSD's and to provide spectra which match the design spectra to a satisfactory degree.

With the model and the input forcing function defined, the last piece of input information requiring specification was the definition of damping. In the response spectrum calculations N-411 modal damping was used. That definition of damping could not be used in the proposed ANSYS analysis. Instead, for the non-linear analysis two coefficients, α and β, which quantify system damping as a function of the system mass and stiffness matrices, must be defined. The coefficients α and β were selected to match N-411 damping at the frequencies of 7.7 H_z and 20 H_z. This provided a reasonable but not exact correspondence to N-411 damping over the frequency range 7 through 30 H_z, with the ANSYS damping being greater than 5% at lower frequencies and less than 2% at higher frequencies. The selected values for α and β were 4.8 and 0.0000143 respectively.

A. ANSYS Non-Linear Analysis

With all model and forcing function parameters defined, the non-linear time history analysis was performed. In the analysis the following parameters and options were used. A solution time step of 0.0005 sec. (should be sufficient to capture a 200 H_z event). The Newmark implicit direct integration solution option with δ=0.5 and δ=0.25 (minimizes numerical damping). The Newton Raphson initial stiffness option, KAY(9)=3 (stiffness matrix is only reformed when the status of any gap element is changed). KEYOPT(3) set to one to account for the additional flexibility of bend elements. The plasticity convergence criterion was set at 0.01. This criterion defines the allowed global system force unbalance after each iteration and was selected after several trial runs.

The output results were quite extensive. Selected displacements, force and stress results with comparisons to the corresponding GAPPIPE response spectrum results are presented in Tables 4, 5, and 6.

The displacement results, Table 4, are presented corresponding to each piping section as defined in Table 1. For each section displacements are presented for each node for which a maximum displacement was predicted in the RLCA GAPPIPE solution. Maximums for each coordinate direction are presented. In the table the number in parenthesis is the corresponding value from the RLCA calculation. As can be seen, the ANSYS and GAPPIPE results compare reasonably well for the X and Y coordinate directions but less well for the Z coordinate direction.

Table 5 presents a listing of the maximum value of each component of reaction force for each support element in the system. This includes the five anchors, the five rod hangers and the eight seismic stops. The corresponding GAPPIPE estimates are listed in the column headed RLCA. For the seismic stops the RLCA estimates are impact forces computed based on the calculated displacements at the stops and the true stop spring stiffnesses (i.e. not the linearized approximations). A review of the table will indicate that the degree of correspondence between the ANSYS and GAPPPIPE results are poor. Except for the seismic stops, the ANSYS estimates of reaction force exceed the GAPPIPE estimates of reaction force by factors ranging from 50% to a order of magnitude. For the seismic stops the trend is reversed with the GAPPIPE estimates exceeding the ANSYS estimates by as much as a factor of five.

Table 6 completes the result presentation with a summary of the maximum predicted pipe stresses for each section. The stresses were computed as indicated with no correction for stress intensification. As with displacements, the listing is for those locations where the GAPPIPE code predicted a maximum. A review of the table will indicate that the correspondence of results is fair with the GAPPIPE estimate of the peak stress exceeding the ANSYS estimate by 10%.

The great disparity of reaction force results, and in particular, the fact that the GAPPIPE estimates of these were so low, was a great concern. The ANSYS input data files were searched in detail for errors but none were found. Discussions were held with the ANSYS computer aid service but they could only recommend that the calculation be repeated using an entirely different approach. The use of different computer codes was also considered. The last two options were rejected as they would require large new investments of resources which could not be accommodated. Finally, a copy of the ANSYS job deck was transmitted to the ANSYS computer aid service for their review.

B. ANSYS Linear Analysis

Given the significant disparities noted it was decided to augment the ANSYS non-linear analysis with linear analyses performed using the ANSYS model. In particular, two response spectrum calculations were made. In one calculation all the seismic stops were eliminated from the model. In the other calculation, all the seismic stops were included with their stiffness set to the closed gap stiffness. The two calculations then bounded the operating configurations of the seismic stops.

The results for the response spectrum runs are shown in Tables 7 and 8. Table 7 provides the displacement results while Table 8 provides the reaction force results. These tables also include a listing of the GAPPIPE and ANSYS non-linear time history results presented earlier. In the table, the column headed RLCA are the GAPPIPE results, the column headed T.H. are the ANSYS non-linear time history results, the column headed RSR are the response spectrum results with all seismic stops closed, and the column headed RST are the response spectrum results with all seismic stops open.

A review of Table 7 shows that the two response spectrum estimates of maximum displacement typically bound or are in reasonable agreement with the GAPPIPE and T.H. results. A review of Table 8 shows the same level of agreement between the response spectrum estimates of reaction force and the GAPPIPE estimates for those forces. The agreement with the T.H. estimates of the reaction force are poor. In many instances the T.H. estimates exceed the response spectrum results by large amounts. The disparities are in fact comparable to the disparities noted earlier between the GAPPIPE and T.H. results and which were the source of concern. These response spectrum results lend credibility to the GAPPIPE results and discredit the ANSYS non-linear analysis results, at least for the estimates of support forces.

C. Follow On

At a later date the ANSYS computer aid service group advised BNL as follows:

a) A run made using the BNL ANSYS file reproduced the BNL results including the high reaction force estimates.

b) Using a small subsection of the model and the same computational parameters again resulted in high reaction force estimates.

c) Using the subsection model and progressively smaller time step sizes produced estimates of the reaction forces which were progressively smaller.

   A reduction of the time step size by a factor of 250 produced a reduction of the original force estimate by a factor of 100.

d) Based on the above, the time step used in the BNL analysis was far too coarse.

e) The difficulty in part lies in the fact that ANSYS uses the enforced ground displacement as input. Specification of enforced displacements is not recommended when using the Newmark Beta method since this method introduces discontinuities in acceleration.

f) The model should be reordered to minimize the wavefront. Reordering could reduce the CPU time by a factor of 100.

D. Observations

The estimates of support force developed in the ANSYS non-linear time history analysis are not considered reliable. The reduction in integration time step size apparently needed to develop reliable results would burden the computing capacity at BNL and is considered impractical. The estimates of piping system displacements and the resultant stresses predicted with this analysis are comparable to those predicted with the response spectrum methods and may be more reliable.

The response estimates developed with the two bounding linear response spectrum analyses show good agreement with the response estimates developed with the GAPPIPE code. For many response quantities the GAPPIPE result was bounded between the two response spectrum estimates. For those instances where the GAPPIPE estimates fell out of the bounds of the two response spectrum solutions, the correspondence between solutions were still relatively close. The good correlation achieved in this phase of the study lend confidence in the adequacy of the GAPPIPE response estimates.

5. ANSYS VERIFICATION ANALYSIS

Owing to the poor response predictions developed with ANSYS it was decided to perform some analysis to verify the capability of the ANSYS non-linear time history analysis option with gapped spring elements. A problem selected for this purpose was a three dimensional pipe bend supported by two anchors and restrained by three gapped springs. This problem was used by researchers at Westinghouse (11), RLCA and BNL (12) to test analysis options based on the pseudo force method of analysis. The results developed by the three organizations were essentially identical and can serve as a benchmark.

A sketch of the system is shown in Figure 16. A computer generated isometric of the finite element model of the system is shown in Figure 17. As shown, the three gapped springs are located at nodes 4, 6, and 10 and each acts in a different coordinate direction. The excitation is introduced by three time varying forces acting at nodes 4, 6, and 10 in line directions to close the gaps. The time history traces of the applied forces are shown in Figure 18. The gap size and spring stiffness at the three gapped springs are 0.250 in./2.0 E+06 lb./in., 0.125 in./3.0 E+06 lb./in. and 0.062 in./1.5 E+06 lb./in. for nodes 4, 6, and 10 respectively.

The predicted spring force versus time for each of the gapped spring elements are shown in Figures 19, 20, 21. These were developed using the same time step (0.0000625) as was used in the pseudo force test runs. Each figure shows in fact two time history traces, one corresponding to the ANSYS run and one corresponding to the BNL pseudo force run, overlayed on one another. As will be noted, very little indication that there are two traces is apparent indicating the good agreement of results achieved for the gapped spring forces.

Table 9 shows the corresponding comparison for anchor forces. The agreement for these parameters is not quite as good. Difference in both the times of peak occurrence and the magnitudes of peaks is apparent. Although the differences are not great they may be indicative of the type of disparity noted in the seismic stop analysis. Unfortunately, the data base for anchor forces is only the BNL pseudo force results and their reliability as benchmark values is less clear.

In summary, for this problem the ANSYS estimates for gap spring forces are in excellent agreement with the "Benchmark" results. For anchor forces the agreement is only fair to good, but certainly much better than obtained in the seismic stop problem. The discrepancies, however, may indicate that one might expect larger disparities for more complex systems.

The development of a solution for a second, simpler, verification problem was also attempted. This problem was a cantilever beam whose free end displacements are restricted by gapped springs. This problem was also one of the set used by several researchers to test their implementation of the pseudo force analysis method.

Figure 22 shows a sketch of the problem and the ground acceleration loading function. The 20 inch long beam was modeled with 20 equal length beam elements and 2 gapped spring elements on each side of the beam end, as depicted in Figure 22A. The material and structural properties of the beam were taken as; Young's modulus, 30 x 10^6 psi, Poison's ratio, 0.3; cross section, 2" x 3"; moment of inertia, 2 in^4; and mass density of 0.0042 $lb/sec^2/in$. The gap clearance was 0.5 x 10^{-5} in., and the spring stiffness was 2 x 10^5 lb/in. The excitation was the ground motion acceleration time history depicted in Figure 22B.

Several attempts were made to develop a solution to this problem. In the first attempt, the ground motion acceleration record was used as input and the integration time step was taken as 0.00003125 seconds, the value used by researchers in the pseudo force investigations. Since poor results were achieved, the initial attempt was followed by several more, each with a finer integration time step, ending when a time step 1/10 the original, or 0.000003125 seconds, was used. The results still being deficient, another tact was then followed. In these new attempts the input excitation was defined as time varying forces acting on each mass point with the values of the force being derived from the acceleration record. This series of calculations was performed for the same time step sizes as used in the initial series. Again, poor results were achieved. Efforts were concluded when calculations with a time step reduced by another order of magnitude yielded different results.

The predicted relative displacement with respect to ground at the cantilever free end for the last and equivalent calculation in each series is shown in Figure 23, with the upper figure corresponding to the acceleration input option and the lower figure corresponding to the force option. Clearly, they are different. The predicted displacement at the free end developed with the pseudo force method, presumably the correct solution, is shown in Figure 24. As can be seen, there is little apparent correspondence between the solutions developed with ANSYS and the pseudo force result. Close examination reveals that the force input solution at least shows correspondence of the number of peaks and valleys in the solution as compared to the pseudo force solution.

For this problem, the verification attempts were all a failure. Possibly, if the attempts had been continued with finer and finer integration time steps, an improvement in results might have been achieved. However, that option was impractical given the resources available.

This verification problem represented a closer parallel to the Reactor Coolant Bypass line than the first problem in that the forcing function was a ground motion acceleration time history. These poor results coupled with the poor results obtained for the bypass line may be indicative of a deficiency in ANSYS for this mode of excitation.

6. CONCLUSIONS

The evaluation followed two phases; a review of the theoretical basis for the equivalent linearization method and its implementation into the GAPPIPE computer code and verification of GAPPIPE through confirmatory analyses. It was determined that the method had been investigated by many researchers who established a theoretical basis for the method, explored its range of applicability and quantified the accuracy to be expected in its application. The adequacy of its implementation into the GAPPIPE code was demonstrated by the facility with which the code could handle various problems and the correspondence of its response predictions with test results. The confirmatory evaluations, although compromised to some extent by the poor performance in the non-linear calculational mode, confirmed that the GAPPIPE code did provide acceptable estimates of system response.

Based on the evaluation, the following observations and conclusions are made:

- Properly designed seismic stops (gapped supports) can be as effective as snubbers in controlling seismic motions.

- Acceptable estimates of the response of systems incorporating gapped supports can be made using an equivalent linearization methodology.

- The implementation of the linearization methodology into the GAPPIPE computer code appeared correct and competently performed.

- Response estimates developed with GAPPIPE should exhibit an accuracy consistent with the response spectrum methodology.

- The support force estimates developed with GAPPIPE should be interpreted as time averaged approximations of these quantities.

- Accurate estimates of instantaneous or peak support forces or support force estimates that are in global equilibrium should not be expected from GAPPIPE.

- In general, the method can be expected to provide conservative estimates of support forces.

7. REFERENCES

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REACTOR COOLANT BYPASS LINE MODEL PARAMETER

TABLE 1

SEC	PIPE SIZE (INCHES)	NODE FROM	RANGE TO	# OF ELEMENTS	ANCHOR	VERTICAL SUPPORT	SEISMIC STOPS
1	3/4	1	68	67	1*	49	39, 44,55
2	1 1/2	68	120	53	72	117	98
3	3/4	121	177	57	7	171, 162, 102	151, 147, 157, 170
4	1 1/2	178	202	25			
5	8	203	238	28	203,238		

* Pipe node where support, anchor, or seismic stop is located.

TABLE 2

COMPARISON OF NATURAL FREQUENCY SOLUTIONS FOR REACTOR COOLANT SYSTEM BYPASS LINE (LOOP 4) CALCULATED FROM TWO DIFFERENT COMPUTER PROGRAMS

MODE	B.N.L (ANSYS) FREQUENCY (CYCLES/SEC)	E.C.L.A (GAPPIPE) FREQUENCY (CYCLES/SEC)
1	5.052	5.052
2	5.840	5.840
3	6.266	6.266
4	7.523	7.538
5	7.791	7.817
6	8.990	8.990
7	9.770	9.771
8	10.449	10.458
9	11.058	11.061
10	14.148	14.186
11	14.694	14.701
12	15.160	15.167
13	15.914	15.924
14	16.846	16.979
15	17.470	17.470
16	18.813	18.854
17	19.285	19.324
18	19.966	19.989
19	20.245	20.278
20	20.837	20.842
21	21.406	21.413
22	23.056	23.061
23	23.848	23.871
24	26.478	26.478
25	26.691	26.696
26	27.767	27.767
27	29.843	29.826
28	31.225	31.224
29	32.446	32.447
30	34.555	34.570

TABLE 3

SEISMIC STOP PARAMETERS

NODE LOCATION	SUPPORT STIFFNESS STOP CLOSED (LB./IN.)	STOP LEFT SIDE GAP (IN.)	STOP RIGHT SIDE GAP (IN.)	GAPPIPE LINEAR ESTIMATE (LB/IN.)
39	15,000	0.400	0.000	1042
44	5,000	0.000	0.810	518
55	2,800	0.000	1.250	200
98	5,000	0.000	0.910	421
147	15,000	1.160	0.000	1311
151	15,000	0.000	0.100	1160
157	2,800	0.000	0.830	200
170	2,800	0.000	1.384	246

TABLE 4 - NODAL DISPLACEMENTS (IN.)

SEC	NODE	X	Y	Z
1	47	0.84 (0.92)*		
	45		0.13 (0.14)	
	58			0.95 (0.78)
2	100	0.49 (0.50)		
	105		0.05 (0.1)	
	105			0.95 (0.35)
3	161	0.60 (0.52)		
	121		0.12 (0.20)	
	155			0.63 (0.45)
4	183	0.25 (0.22)		
	188		0.15 (0.13)	
	177			1.01 (0.37)
5	221	0.13 (0.14)		
	217		0.11 (0.10)	
	220			0.17 (0.16)

* Max. nodal displacement (in inches) values in parenthesis are RLCA results.

TABLE 5 - REACTION FORCES
(lbs. or in./lbs.)

TYPE	NODE	COMPONENT	RLCA	BNL
ANCHOR	1	X	76	2,229
		XX	548	728
		Y	120	179
		YY	3,402	7,501
		Z	91	265
		ZZ	4,695	6,027
ANCHOR	7	X	82	846
		XX	4,098	4,385
		Y	133	145
		YY	3,376	6,666
		Z	34	1,950
		ZZ	2,857	2,220
ANCHOR	72	X	119	2,407
		Y	119	2,045
		Z	134	2,003
		XX	4,920	17,130
		YY	4,890	7,025
		ZZ	6,130	21,660
ANCHOR	203	X	2,615	115,100
		Y	3,091	28,540
		Z	1,494	110,800
		XX	167,373	493,600
		YY	152,435	890,200
		ZZ	132,556	540,900

TABLE 5 - REACTION FORCES
(lbs. or in./lbs.)

TYPE	NODE	COMPONENT	RLCA	BNL
ANCHOR	238	X	3,328	34,730
		Y	5,018	11,530
		Z	3,862	18,940
		XX	177,701	177,800
		YY	383,289	521,500
		ZZ	335,763	471,100
VERTICAL SUPPORT	49		74	340
	102		163	503
	117		316	412
	162		35	182
	171		111	427
SEISMIC STOP	39		506	91
	44		407	113
	55		453	181
	98		618	470
	147		208	134
	151		116	158
	157		267	148
	170		452	281

TABLE 6 - MAX. PIPE STRESSES OF EACH SECTION

SEC	ELEMENT NUMBER	STRESS (ksi)	
		BNL	RLCA
STRAIGHT PIPES			
1	67J	18.5	22.6
2	112I	10.8	9.4
3	177J	20.7	22.5
4	194I	15.8	10.8
5	235J	14.1	9.3
ELBOWS			
1	10I	16.8	15.8
2	95M	10.5	8.2
3	145M	10.7	13.1
4	193J	18.0	10.8
5	209I	9.6	3.2

*No stress intensification factor applied

$$S = \frac{(Mx^2 + My^2 + Mz^2)^{1/2}}{Z}$$

TABLE 7 - MAX. NODAL DISPLACEMENTS (IN.)

SEC	NODE	COMPONENT	RLCA	BROOKHAVEN NATIONAL LABORATORY		
				TH	RSR	RSF
1	47	X	0.92	.84	0.33	0.88
	45	Y	0.14	.13	0.12	0.74
	58	Z	0.78	.95	0.54	1.09
2	100	X	.50	.49	0.53	0.65
	105	Y	.10	.05	0.35	0.06
	105	Z	.35	.95	0.11	1.40
3	161	X	.52	.60	0.34	0.83
	121	Y	.20	.12	0.17	0.2
	155	Z	.45	.63	0.53	1.0
4	183	X	.22	.25	0.22	0.21
	188	Y	.13	.15	0.13	0.13
	177	Z	.37	1.01	0.09	1.51
5	221	X	.14	.13	0.14	0.12
	217	Y	.10	.11	0.1	0.1
	220	Z	.16	.17	0.17	0.16

TABLE 8 - REACTION FORCES
(lbs. or in./lbs.)

TYPE	NODE	COMPONENT	RLCA	BROOKHAVEN NATIONAL LABORATORY		
				T.H.	RSR	RSF
ANCHOR	1	X	76	2,229	75	73
		Y	120	179	142	155
		Z	91	265	54	136
		XX	548	728	589	458
		YY	3,402	7,501	1,843	5,700
		ZZ	4,695	6,027	5,597	6,200
ANCHOR	7	X	82	846	96	268
		Y	133	145	87	159
		Z	34	1,950	87	200
		XX	4,098	4,385	2,468	5,720
		YY	3,376	6,666	3,463	13,285
		ZZ	2,857	2,220	2,196	2,937

TABLE 8 - REACTION FORCES
(lbs. or in./lbs.)

TYPE	NODE	COMPONENT	RLCA	BROOKHAVEN NATIONAL LABORATORY		
				T.H.	RSR	RSF
ANCHOR	72	X	119	2,407	144	171
		Y	119	2,045	122	184
		Z	134	2,003	150	273
		XX	4,920	17,130	5,865	7,216
		YY	4,890	7,025	5,355	11,050
		ZZ	6,130	21,660	6,510	9,250
ANCHOR	203	X	2,615	115,100	2,546	2,005
		Y	3,091	28,540	3,007	2,416
		Z	1,494	110,800	1,496	1,492
		XX	167,373	493,600	105,400	142,840
		YY	152,435	890,200	149,000	125,594
		ZZ	132,556	540,900	130,600	106,103

TABLE 8 - REACTION FORCES
(lbs. or in./lbs.)

TYPE	NODE	COMPONENT	RLCA	BROOKHAVEN NATIONAL LABORATORY		
				T.H.	RSR	RSF
ANCHOR	238	X	3,328	34,730	3,294	2,980
		Y	5,018	11,530	5,007	4,776
		Z	3,862	18,940	3,826	3,746
		XX	177,701	177,800	177,600	166,994
		YY	383,289	521,500	379,600	365,677
		ZZ	335,763	471,100	333,600	296,811
VERTICAL SUPPORT	49	Y	74	340	62	66
	102	Y	163	503	181	154
	117	Y	316	412	280	314
	162	Y	35	182	39	75
	171	Y	111	427	102	163

TABLE 8 - REACTION FORCES
(lbs. or in./lbs.)

TYPE	NODE	COMPONENT	RLCA	BROOKHAVEN NATIONAL LABORATORY		
				T.H.	RSR	RSF*
SEISMIC STOP	39	X&Y	506	91	92	0
	44	X&Y	407	113	103	0
	55	Z	453	181	144	0
	98	Z	618	470	387	0
	147	X&Z	208	134	202	0
	151	Y	116	158	100	0
	157	X&Z	267	148	101	0
	170	Z	452	281	198	0

* The spring elements are removed in this case.

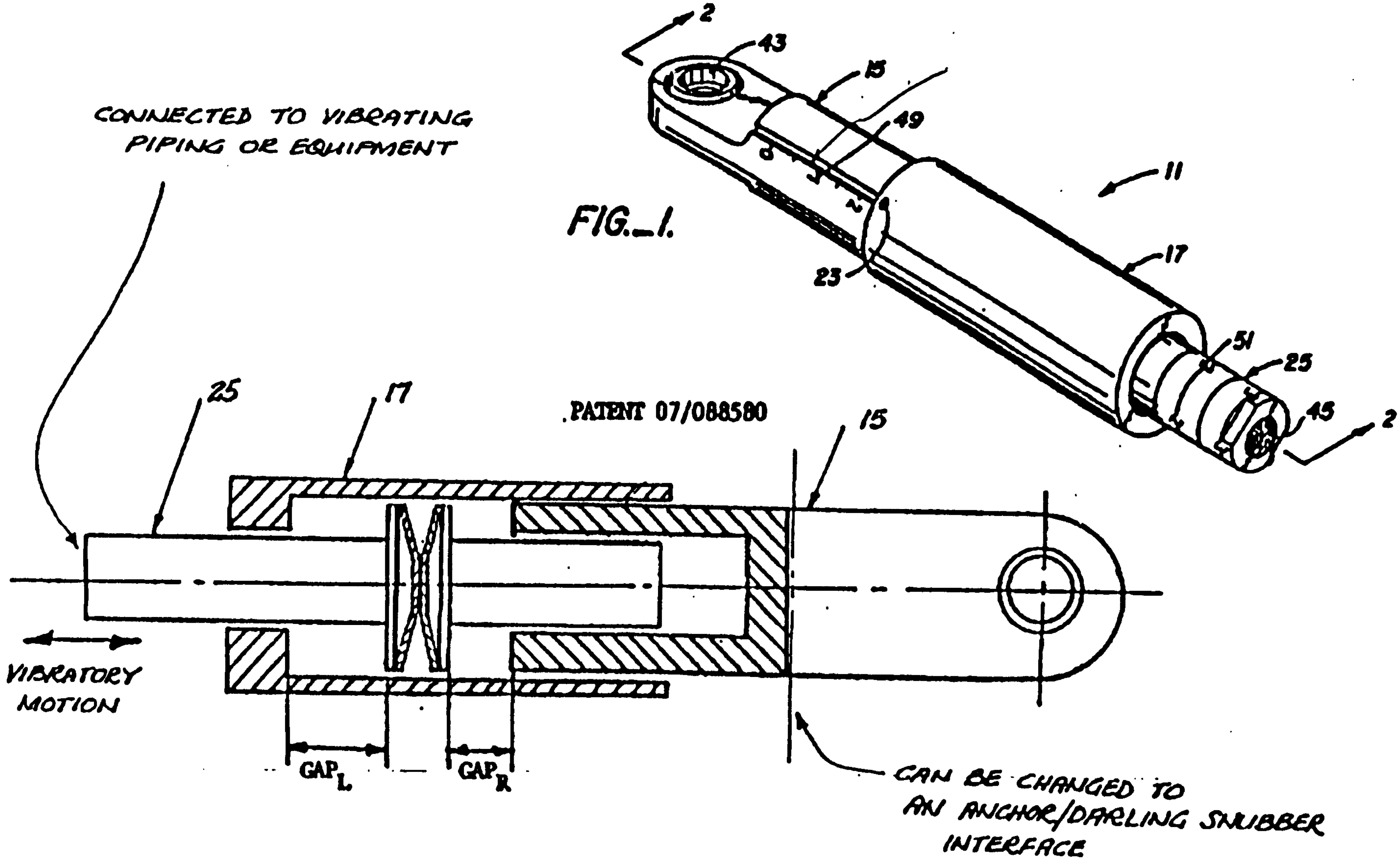
TABLE 9

ANCHOR FORCES COMPARISON FOR HOVGOARD MODEL

		PSEUDO FORCE METHOD		ANSYS	
ANCHOR NODE	FORCE COMP.	VALUE	TIME (SEC)	VALUE	TIME (SEC)
1	FX	1.72E6	0.275	1.80E6	0.283
	FY	1.17E6	0.231	1.30E6	0.101
	FZ	0.57E6	0.262	0.59E6	0.216
	MX	0.07E6	0.193	0.09E6	0.271
	MY	0.67E6	0.156	0.79E6	0.216
	MZ	1.56E6	0.231	1.71E6	0.101
12	FX	1.07E6	0.2	1.25E6	0.203
	FY	0.65E6	0.268	0.88E6	0.224
	FZ	1.05E6	0.193	1.09E6	0.261
	MX	0.19E6	0.15	1.19E6	0.224
	MY	1.39E6	0.193	1.64E6	0.277
	MZ	1.0E6	0.268	0.21E6	0.246

SEISMIC STOP PIPE SUPPORT

DESIGN DESCRIPTION



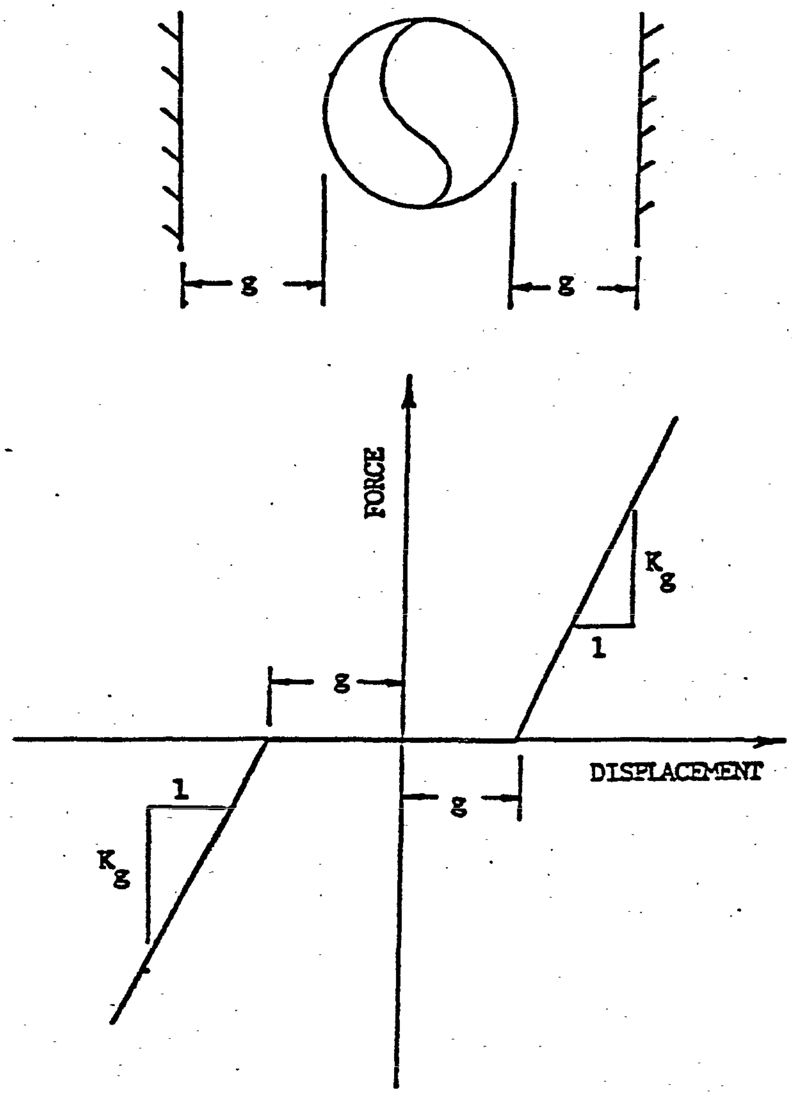


Figure 2 Force-Displacement Relationship of A Symmetric Gapped Support

EXAMPLE1 CONVERGENCE, STOP 11

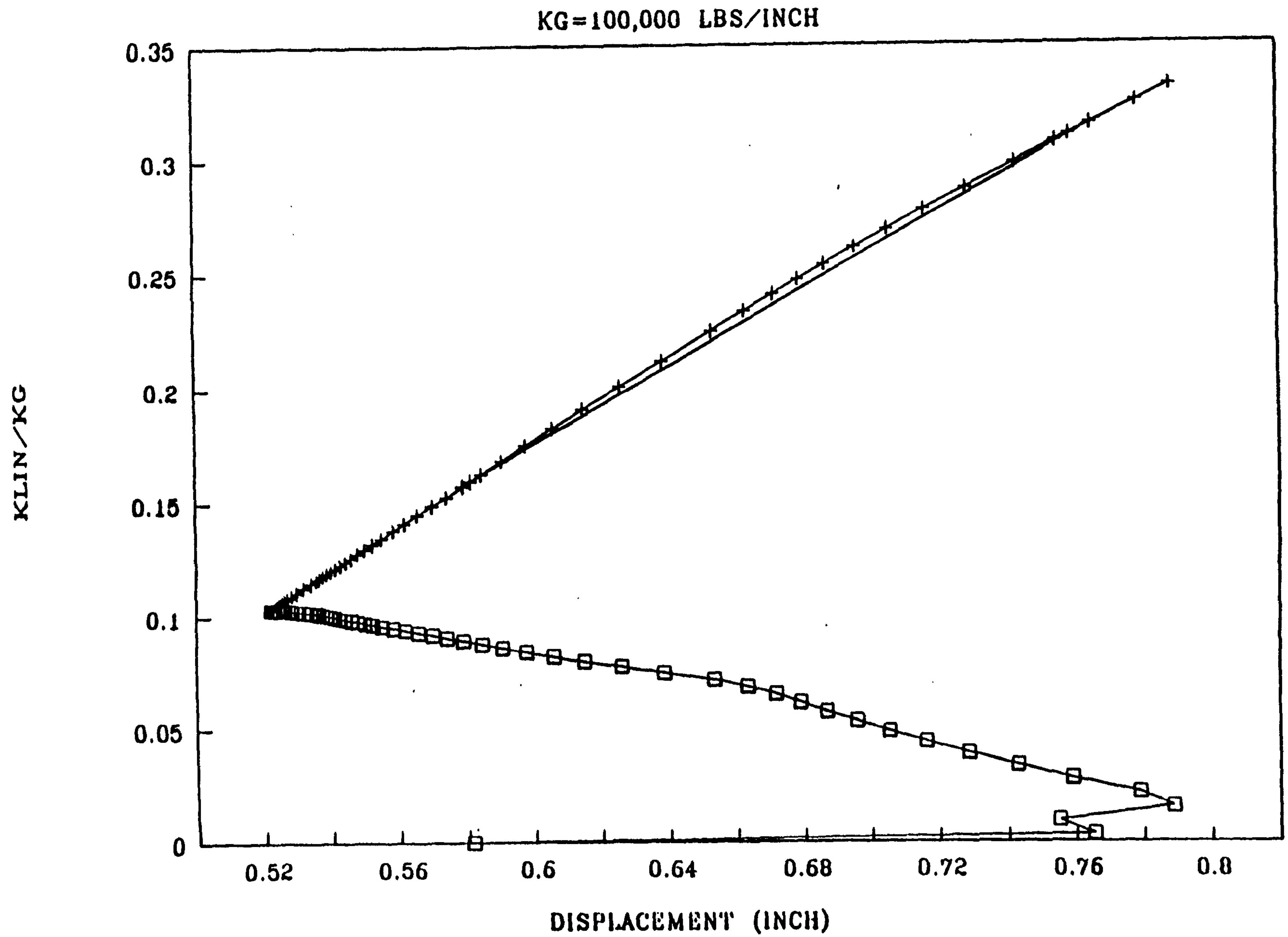


FIGURE 3

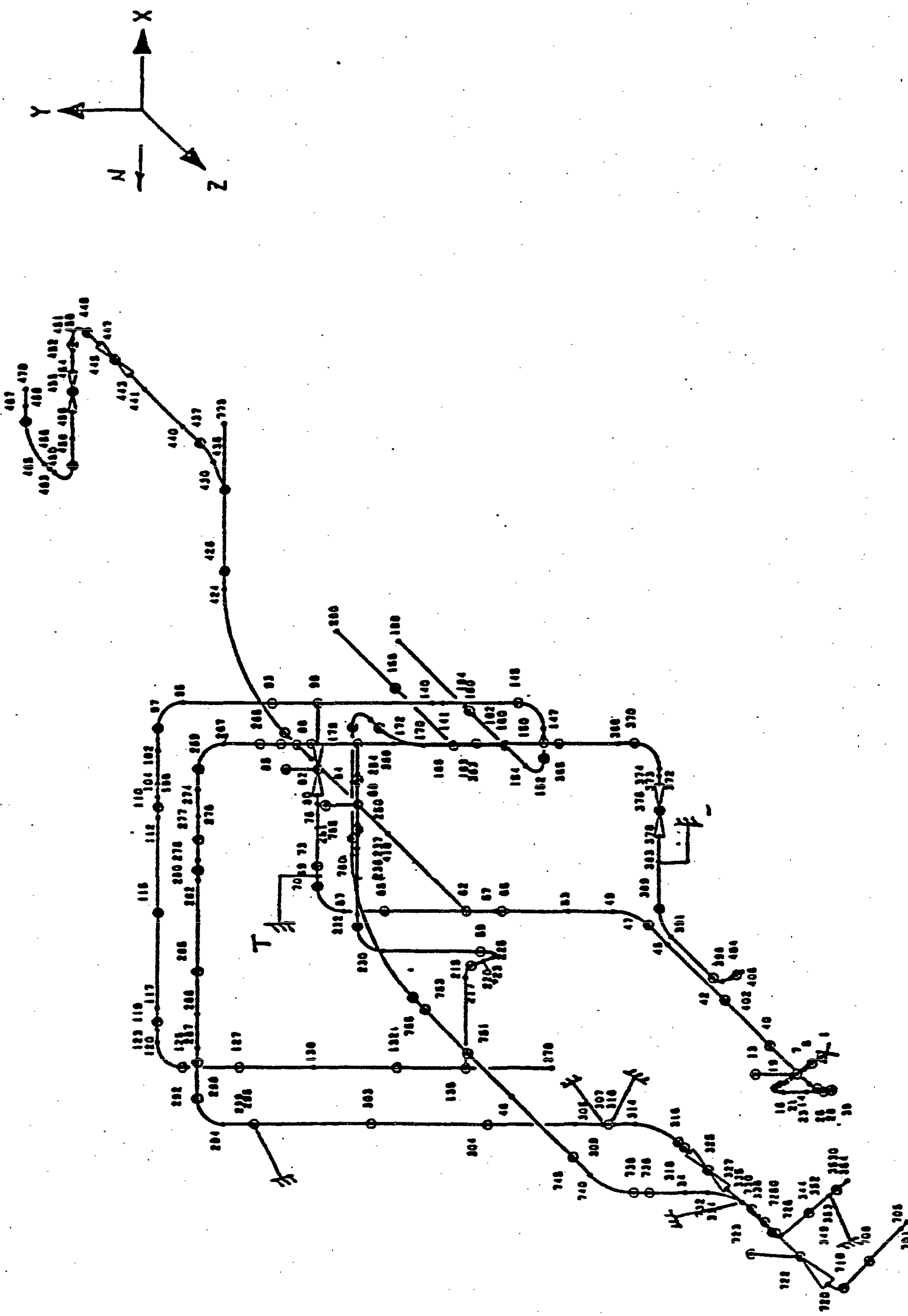


FIGURE 4

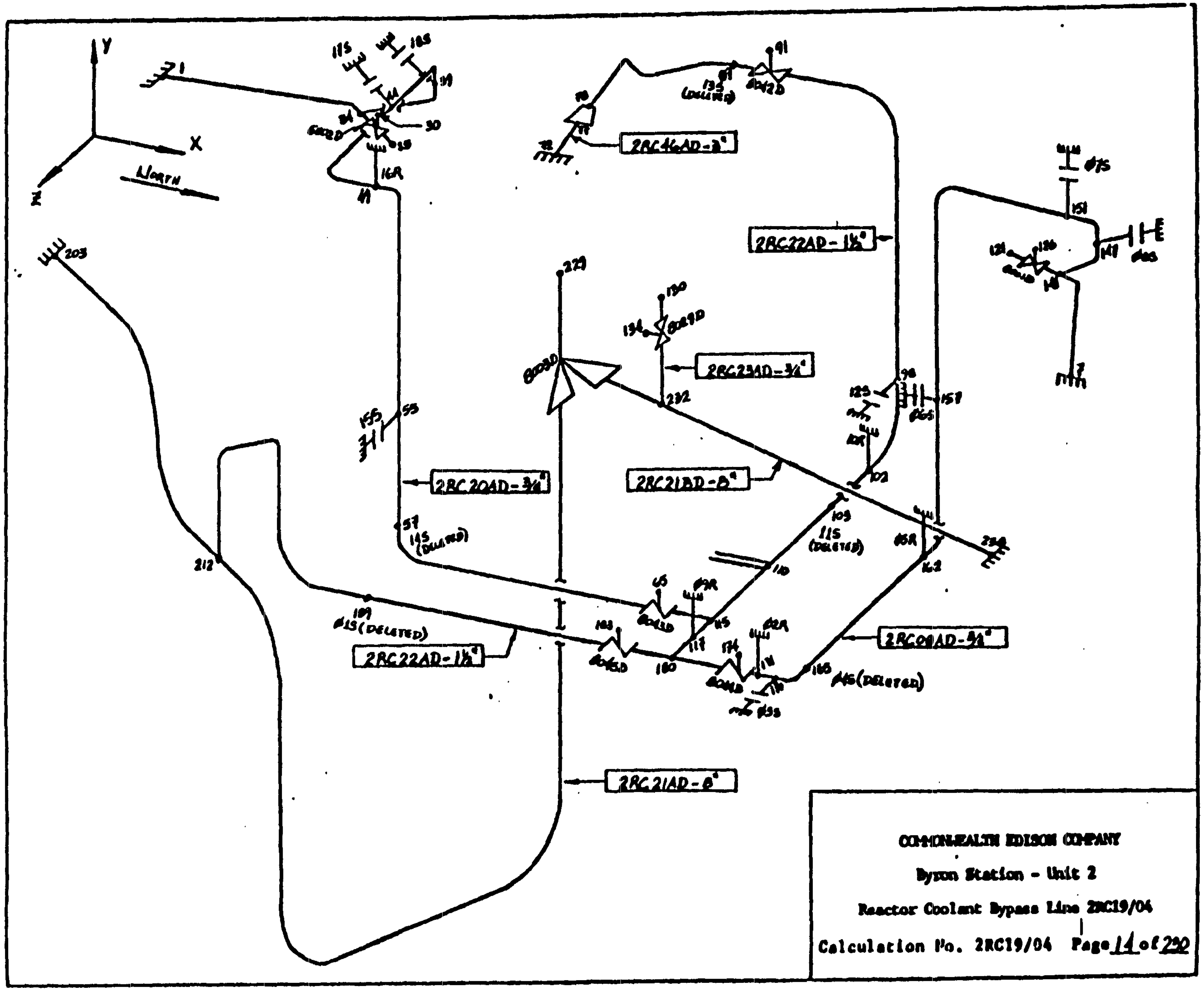
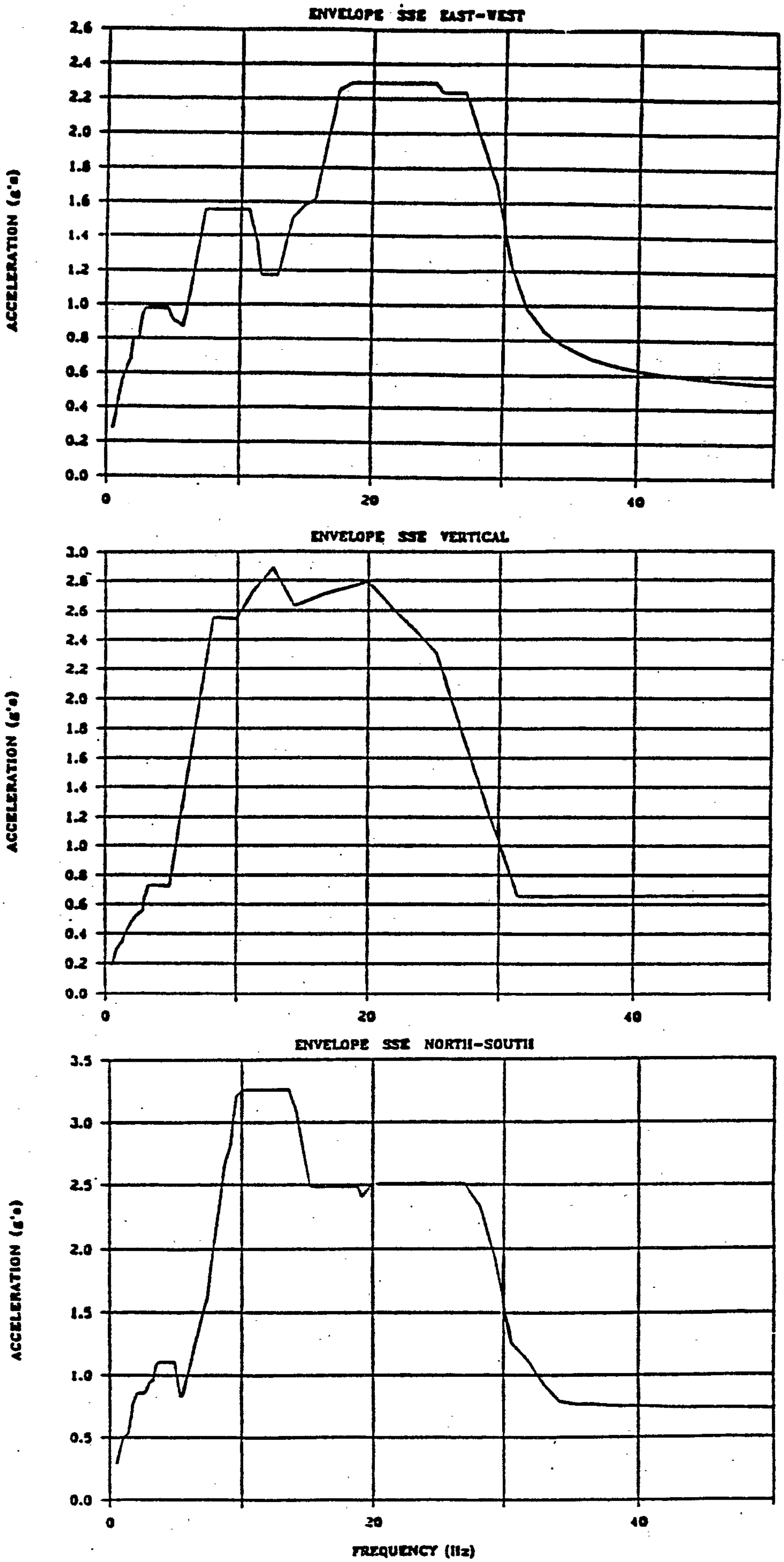

Y
X
Z
NORTH
2RC46AD-3"
2RC22AD-1½"
2RC23AD-¾"
2RC21BD-8"
2RC20AD-¾"
2RC08AD-¾"
2RC22AD-1½"
2RC21AD-8"
115 (DELETED)
145 (DELETED)
#15 (DELETED)
#45 (DELETED)
COMMONWEALTH EDISON COMPANY
Byron Station - Unit 2
Reactor Coolant Bypass Line 2RC19/04
Calculation No. 2RC19/04 Page 14 of 290

FIGURE 5



BYRON UNIT 2 - RCS 2RC19/04

FIGURE 6

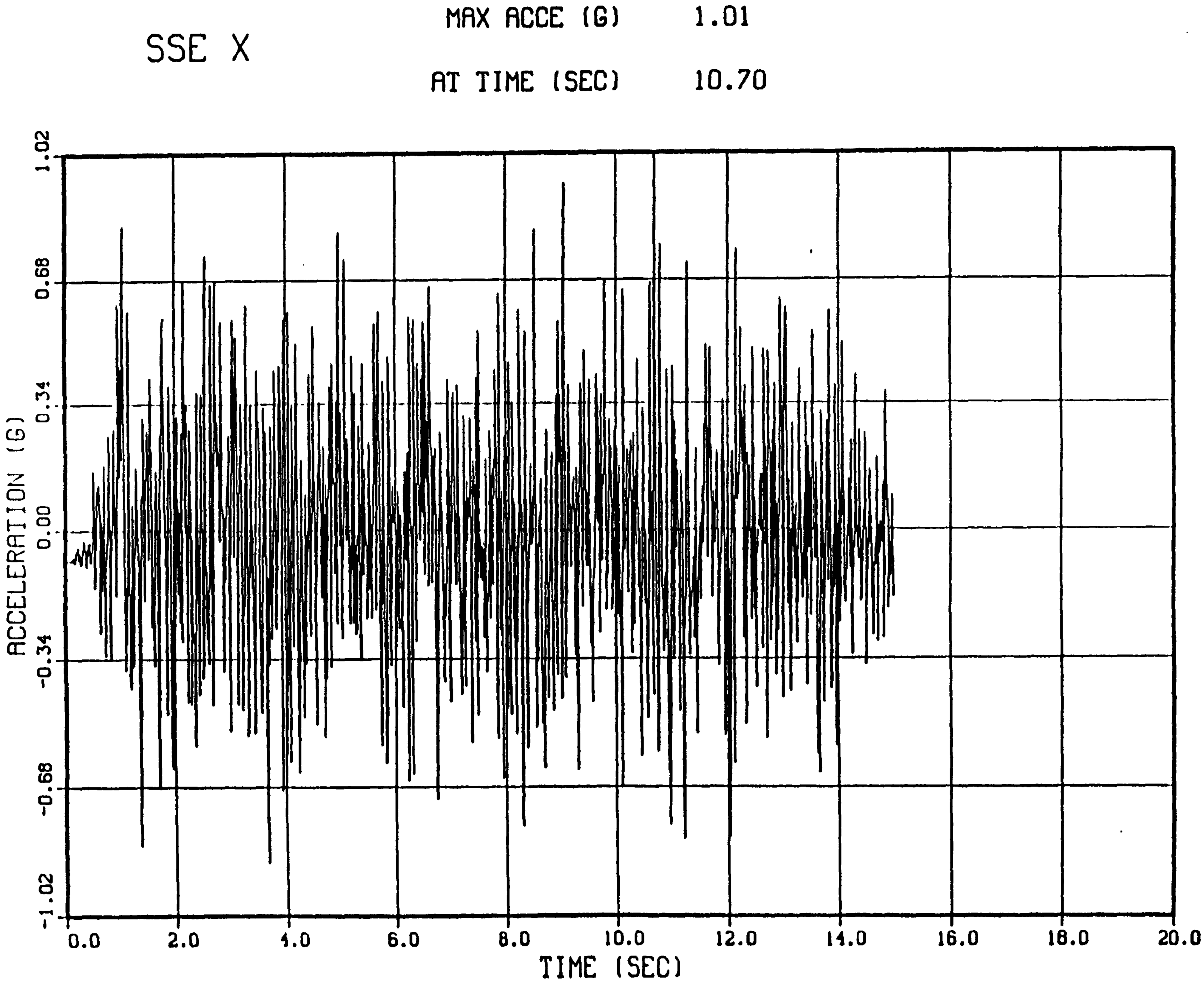

SSE X
MAX ACCE (G) 1.01
AT TIME (SEC) 10.70
ACCELERATION (G)
1.02
0.68
0.34
0.00
-0.34
-0.68
-1.02
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
TIME (SEC)

FIGURE 7

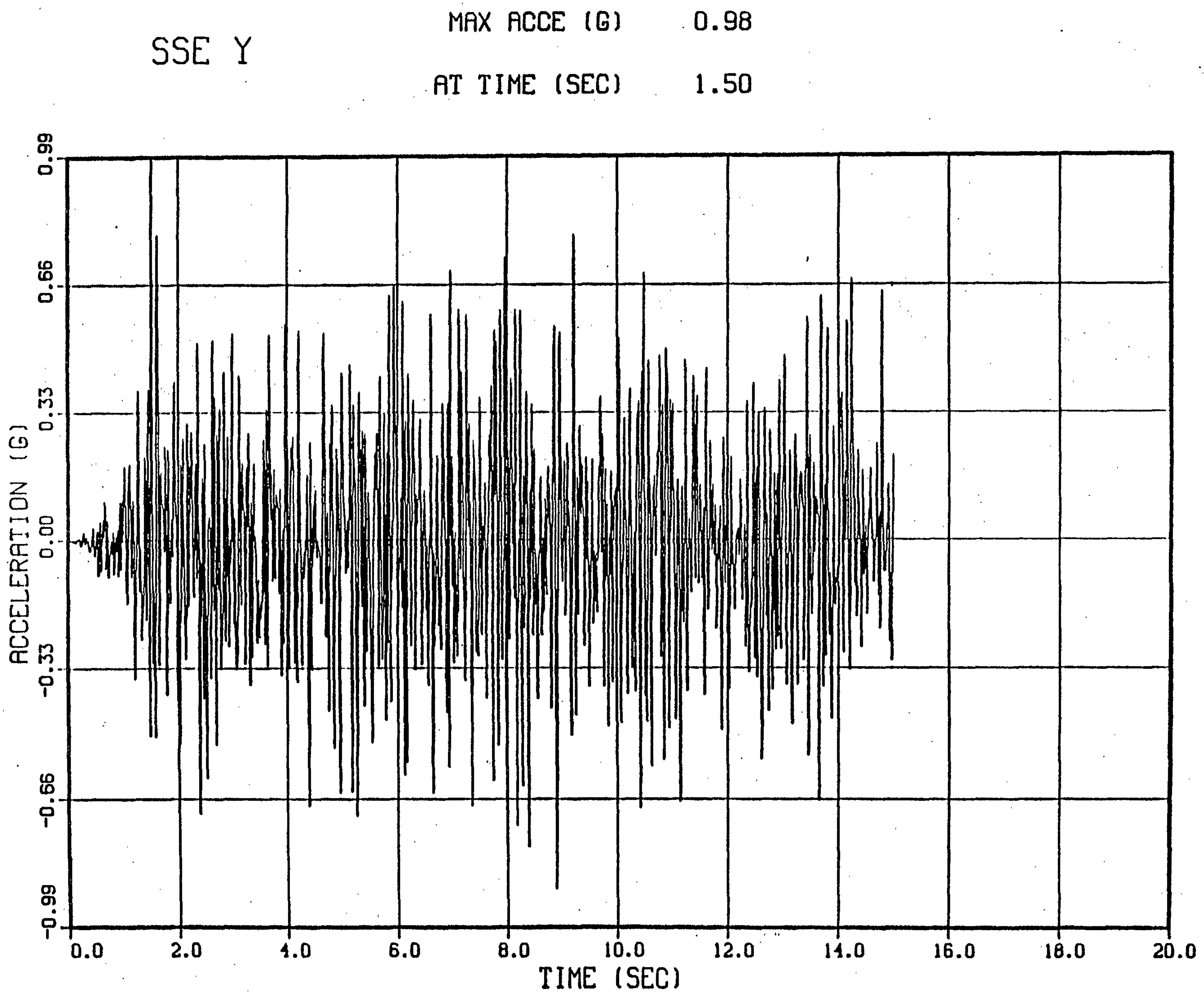

SSE Y
MAX ACCE (G) 0.98
AT TIME (SEC) 1.50
ACCELERATION (G)
0.99
0.66
0.33
0.00
-0.33
-0.66
-0.99
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
TIME (SEC)

FIGURE 8

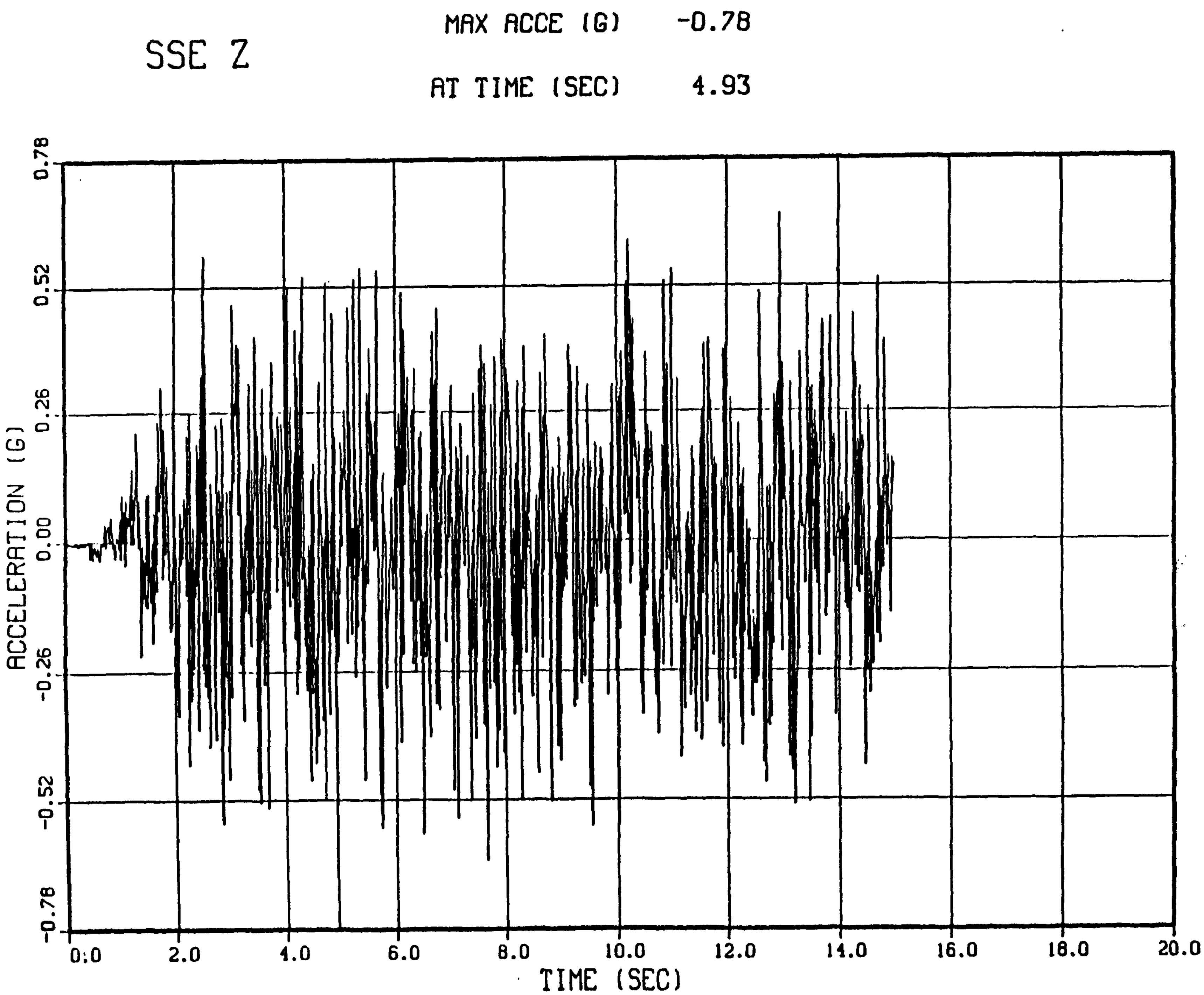

SSE Z
MAX ACCE (G) -0.78
AT TIME (SEC) 4.93
0.78
0.52
0.26
0.00
-0.26
-0.52
-0.78
ACCELERATION (G)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
TIME (SEC)

FIGURE 9

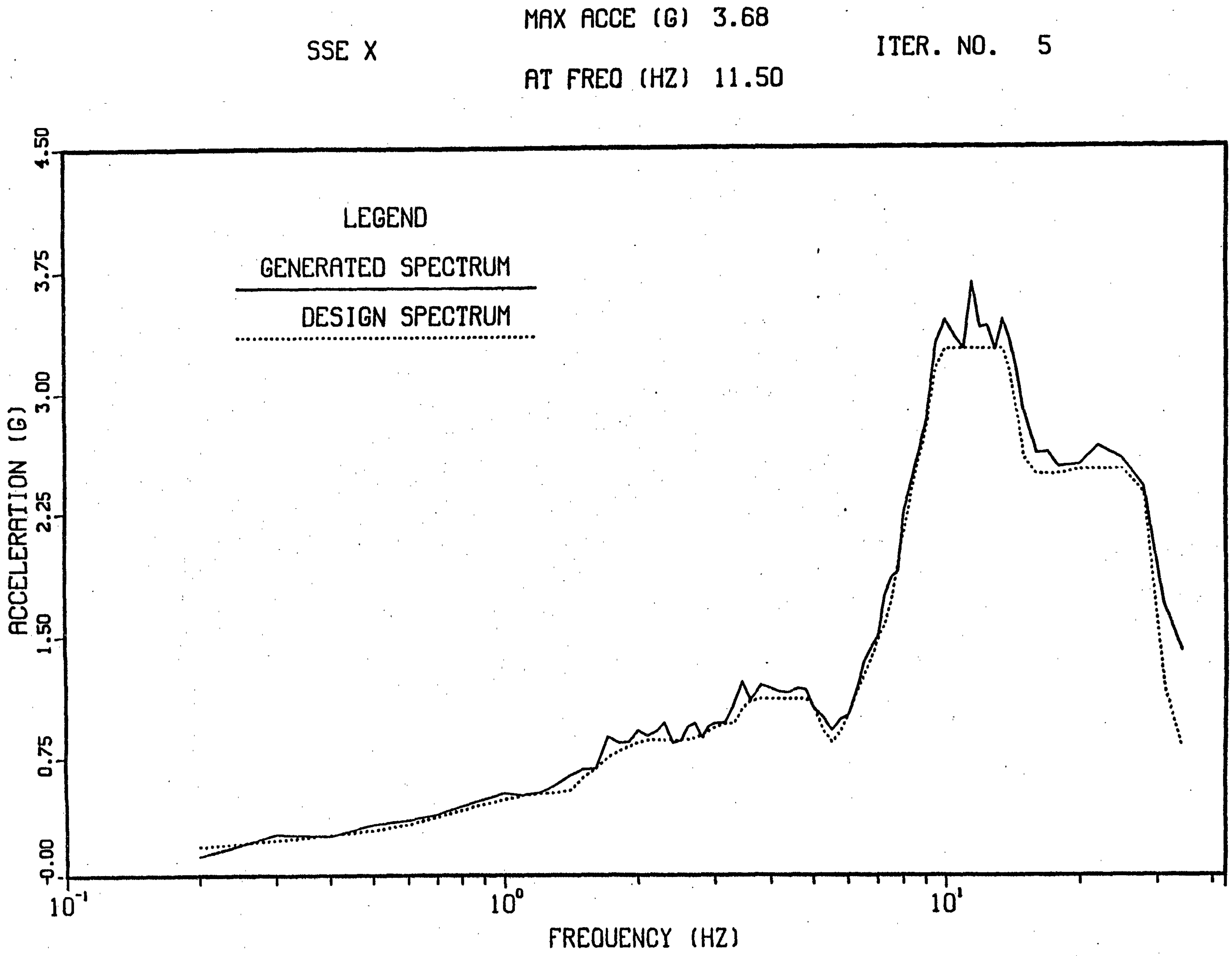

MAX ACCE (G) 3.68
SSE X
ITER. NO. 5
AT FREQ (HZ) 11.50
LEGEND
GENERATED SPECTRUM
DESIGN SPECTRUM
ACCELERATION (G)
4.50
3.75
3.00
2.25
1.50
0.75
0.00
10⁻¹
10⁰
10¹
FREQUENCY (HZ)

FIGURE 10

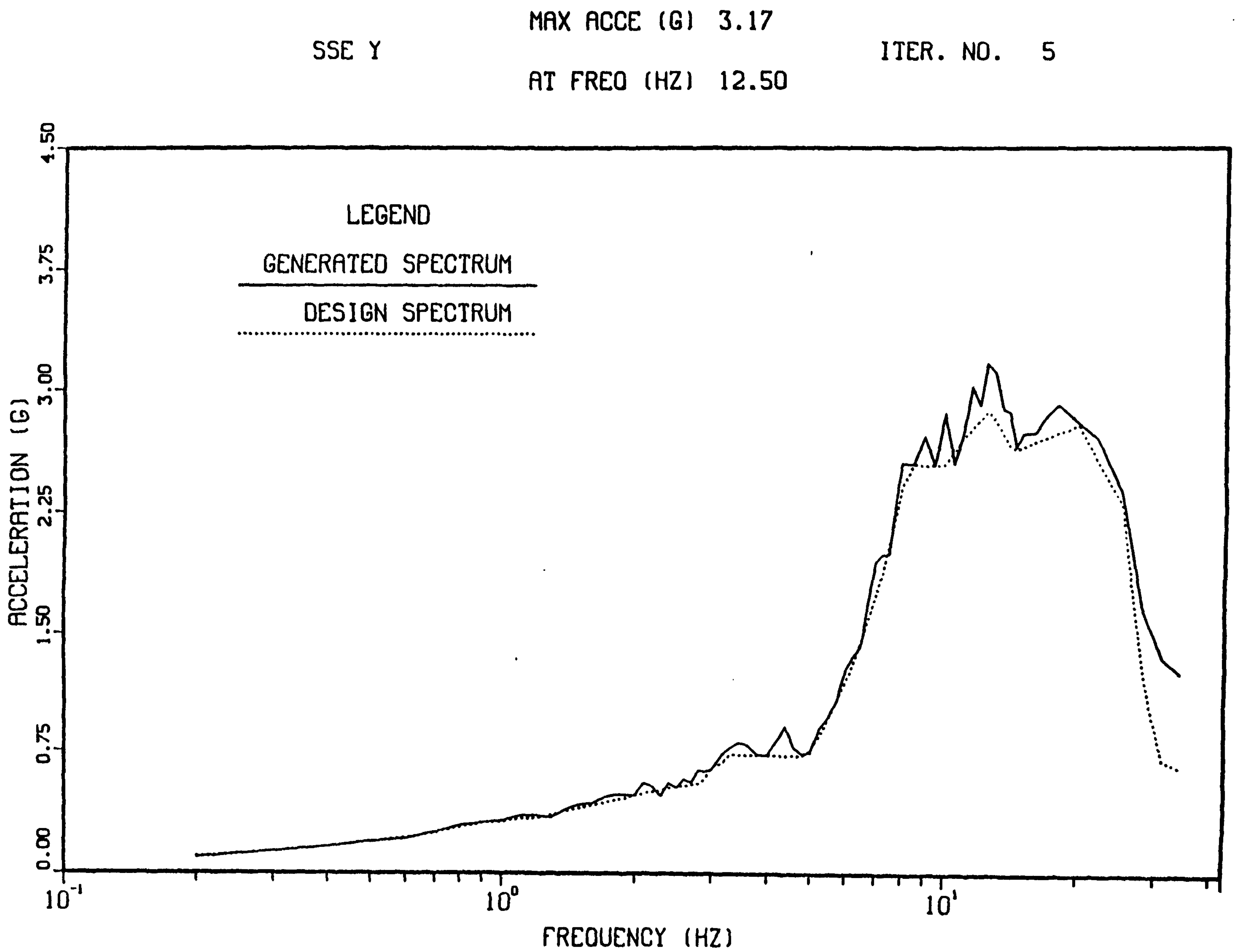

MAX ACCE (G) 3.17
SSE Y
ITER. NO. 5
AT FREQ (HZ) 12.50
LEGEND
GENERATED SPECTRUM
DESIGN SPECTRUM
ACCELERATION (G)
0.00
0.75
1.50
2.25
3.00
3.75
4.50
FREQUENCY (HZ)

FIGURE 11

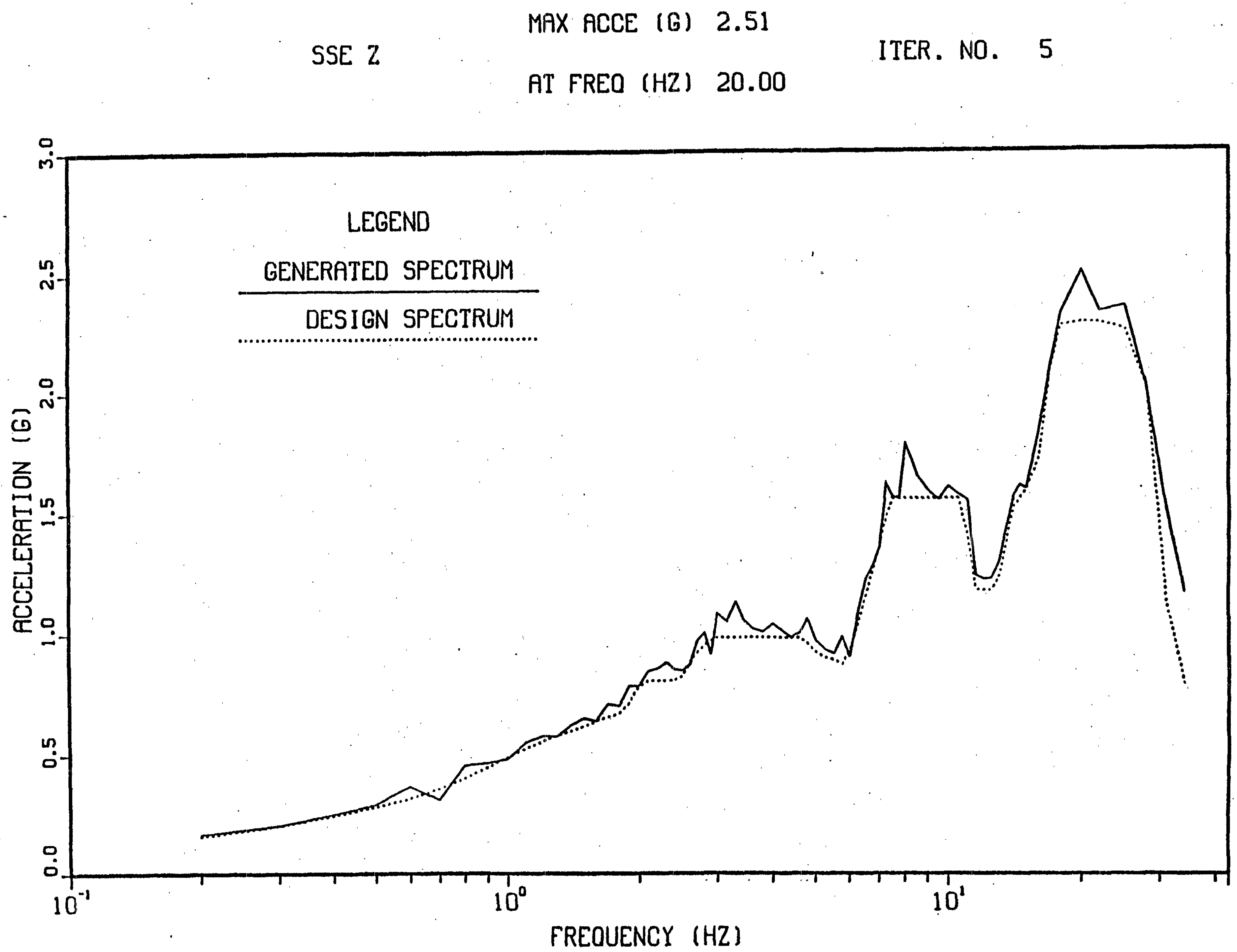

SSE Z
MAX ACCE (G) 2.51
AT FREQ (HZ) 20.00
ITER. NO. 5
LEGEND
GENERATED SPECTRUM
DESIGN SPECTRUM
ACCELERATION (G)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
10^{-1}
10^{0}
10^{1}
FREQUENCY (HZ)

FIGURE 12

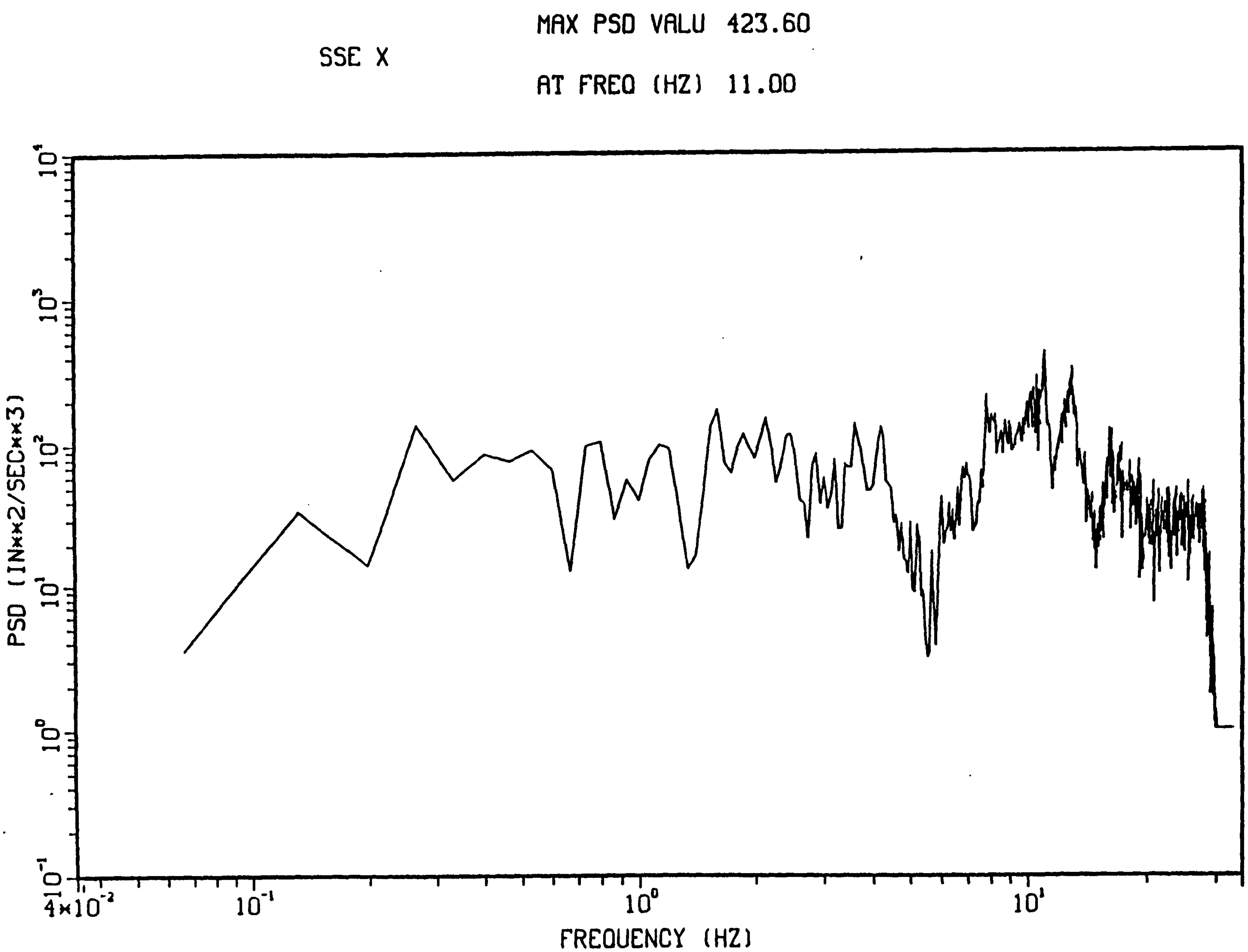

SSE X
MAX PSD VALU 423.60
AT FREQ (HZ) 11.00
PSD (IN**2/SEC**3)
10^4
10^3
10^2
10^1
10^0
10^{-1}
4×10^{-2}
10^{-1}
10^0
10^1
FREQUENCY (HZ)

FIGURE 13

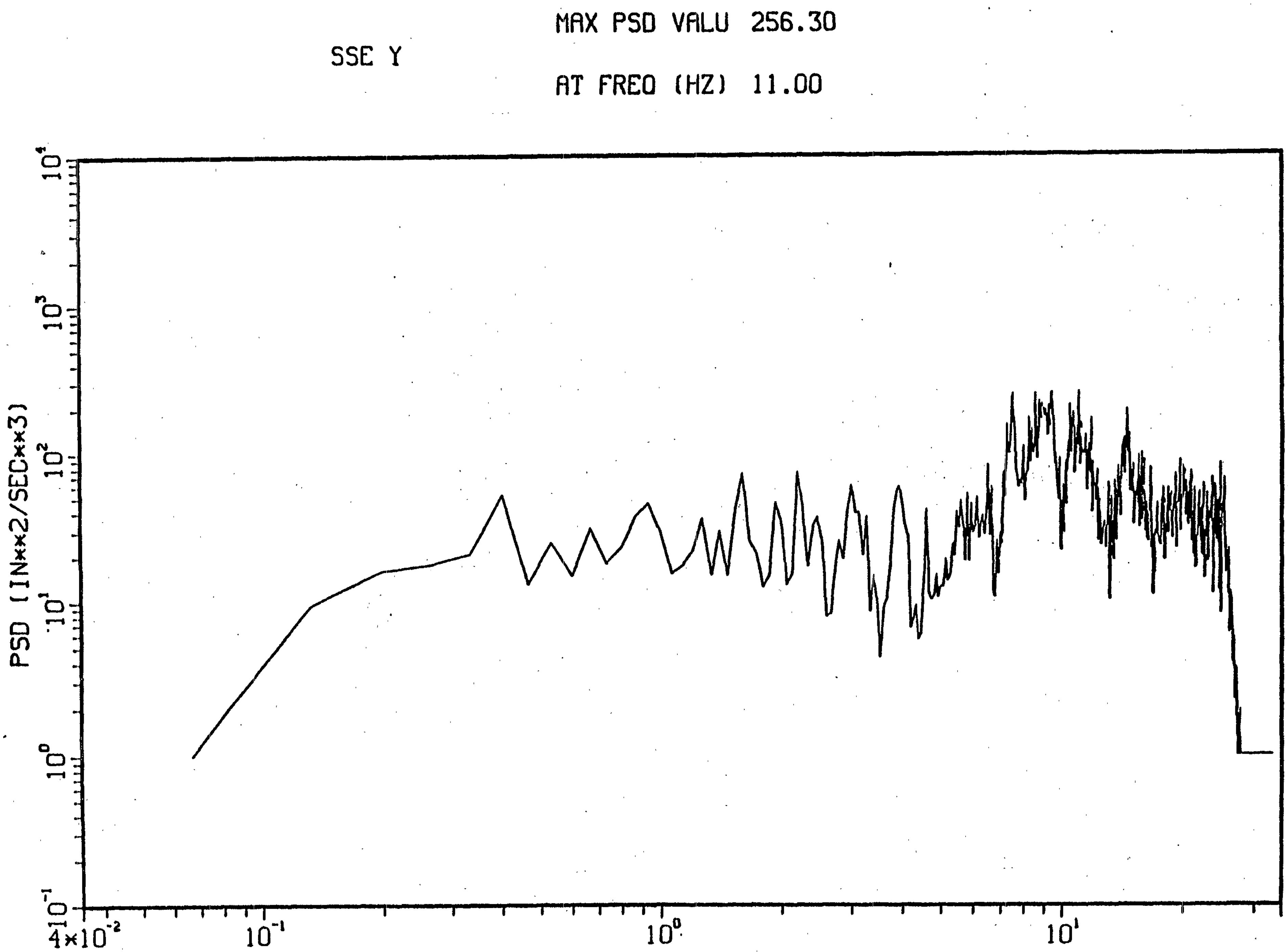

SSE Y
MAX PSD VALU 256.30
AT FREQ (HZ) 11.00
PSD (IN**2/SEC**3)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
4×10^{-2}
10^{-1}
10^{0}
10^{1}
FREQUENCY (HZ)

FIGURE 14

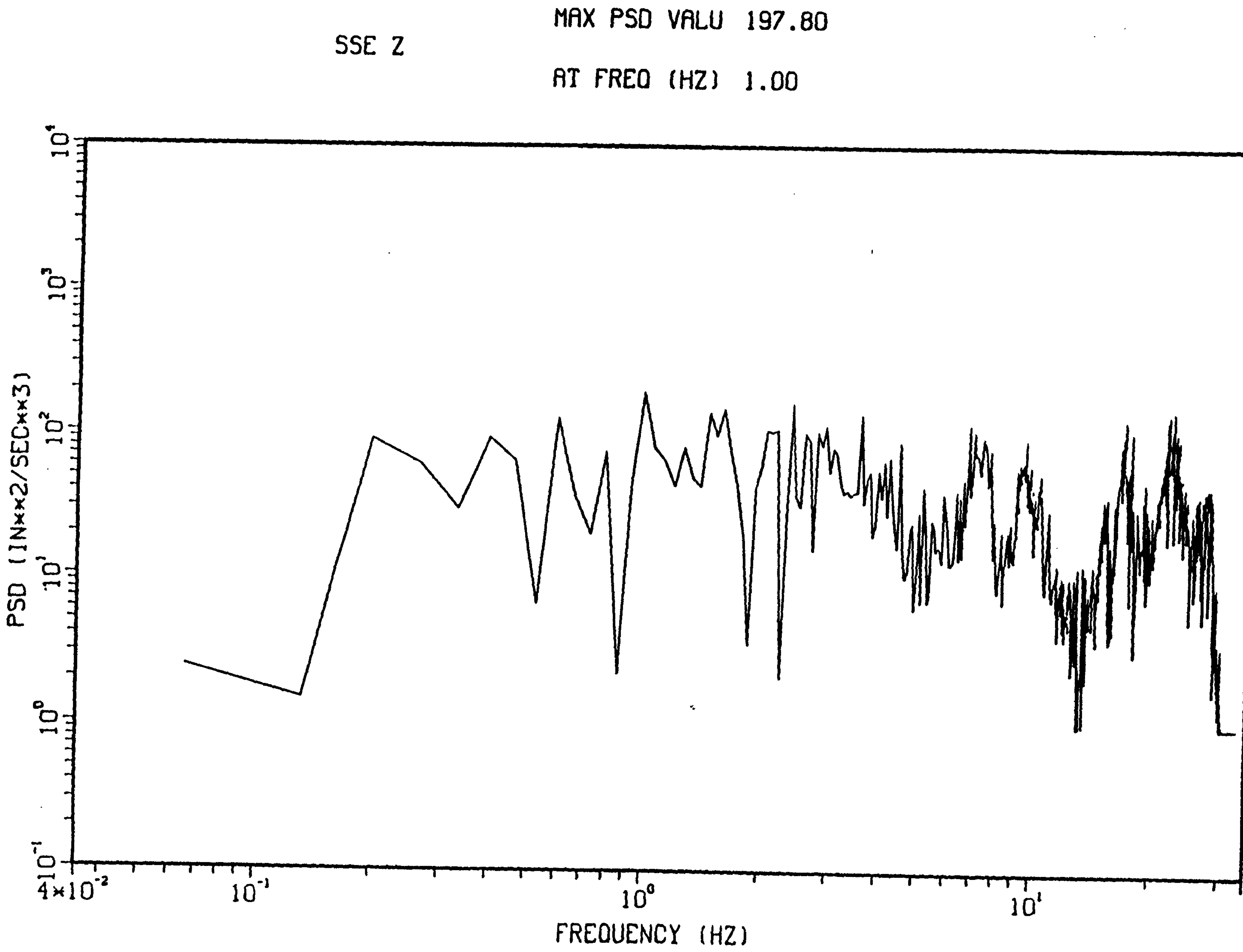
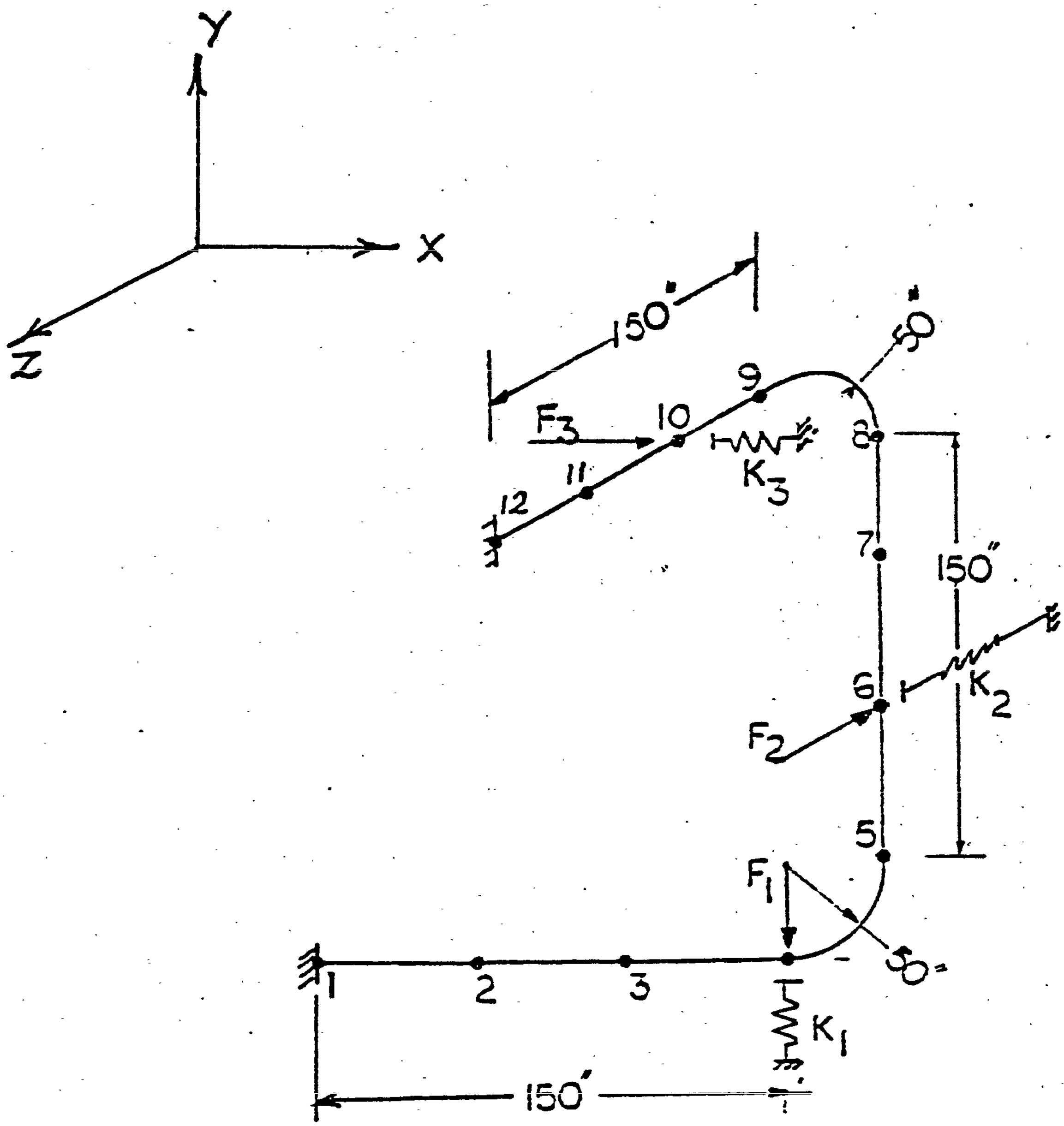

SSE Z
MAX PSD VALU 197.80
AT FREQ (HZ) 1.00
PSD (IN**2/SEC**3)
10⁴
10³
10²
10¹
10⁰
10⁻¹
4×10⁻²
10⁻¹
10⁰
10¹
FREQUENCY (HZ)

FIGURE 15



3D PIPING SYSTEM

FIGURE 16

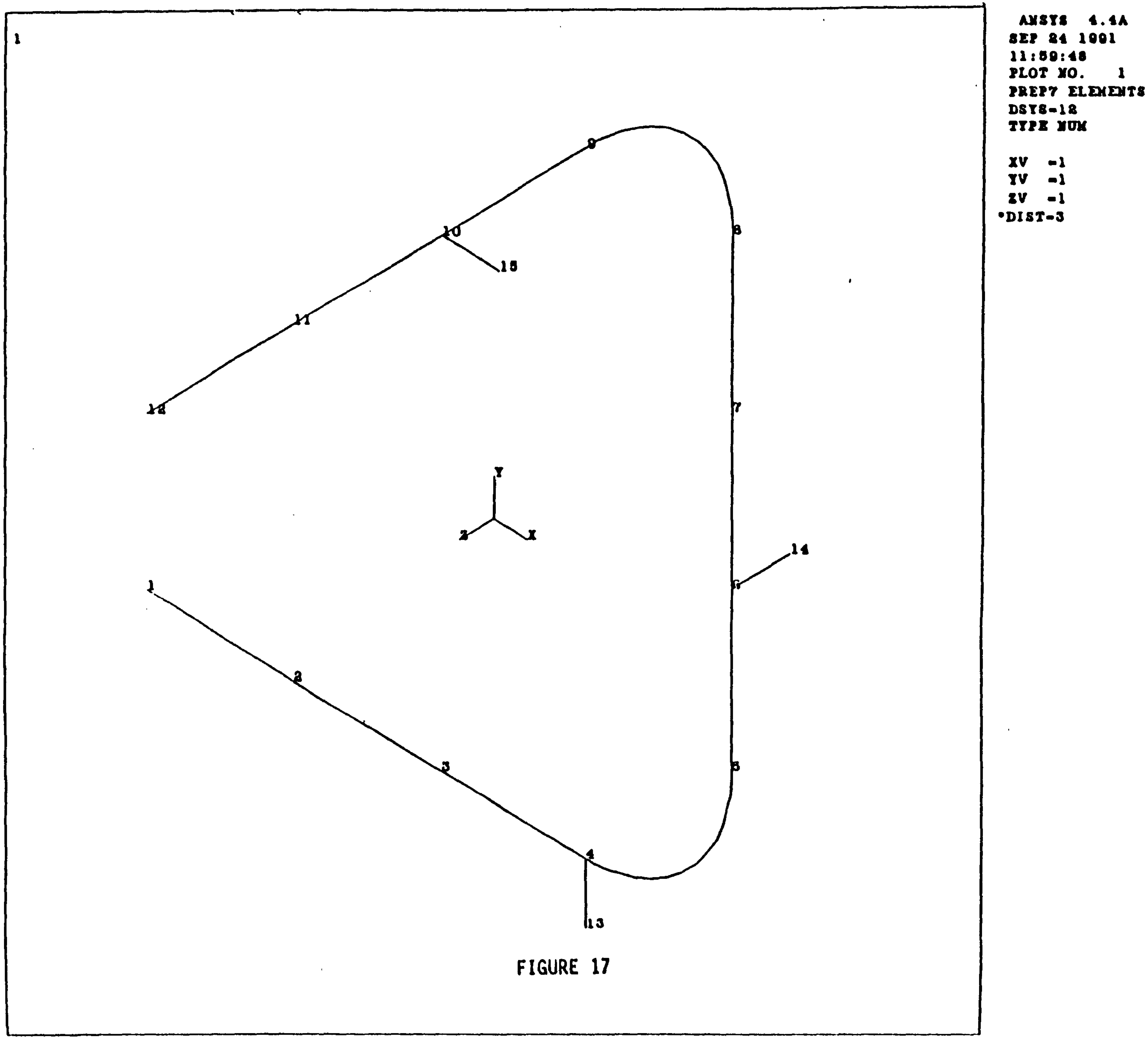
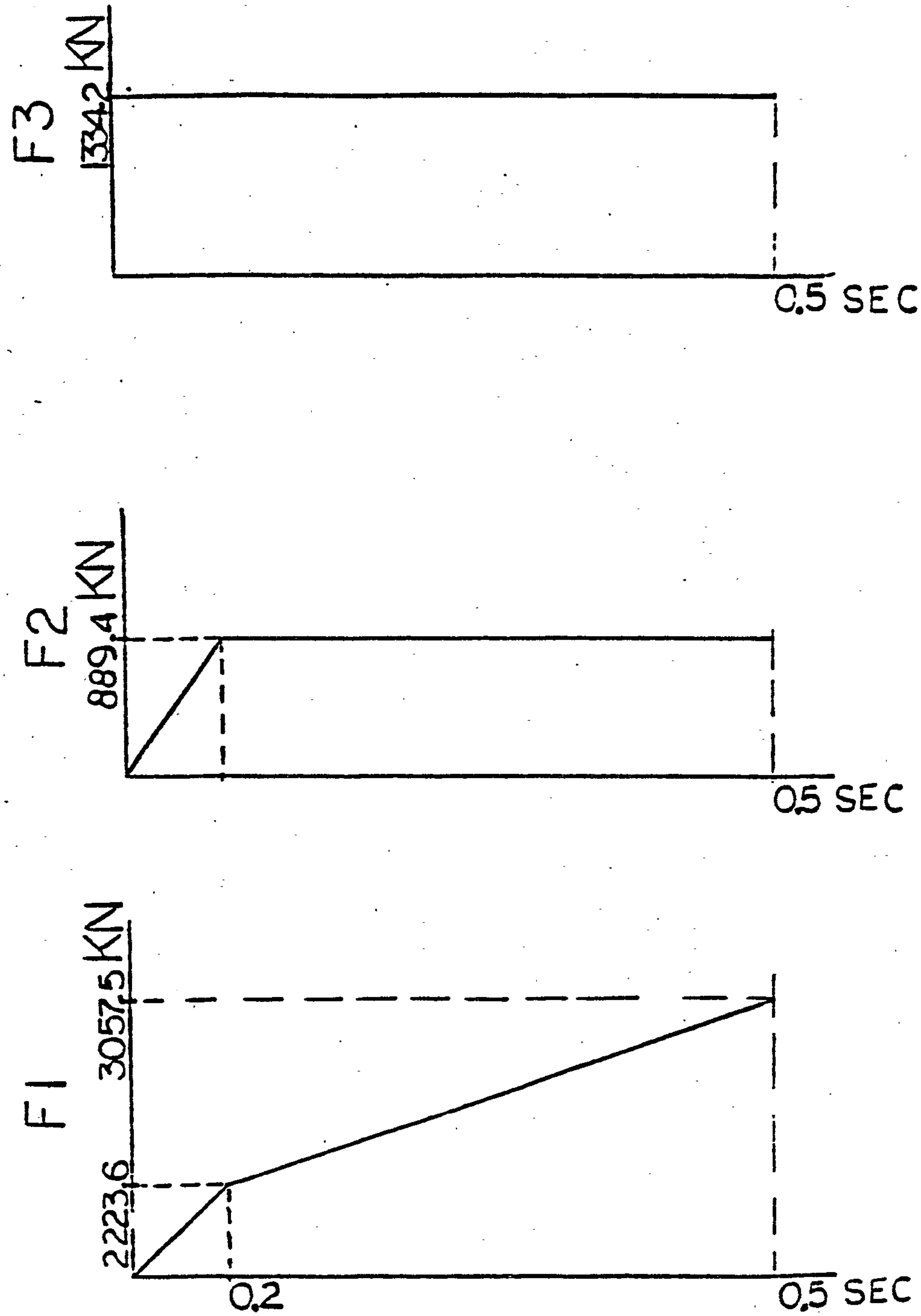

ANSYS 4.4A
SEP 24 1991
11:59:48
PLOT NO. 1
PREP7 ELEMENTS
DSYS=12
TYPE NUM
XV =1
YV =1
ZV =1
*DIST=3
1
2
3
4
5
7
8
9
10
11
12
13
14
15
Y
X
Z

FIGURE 17



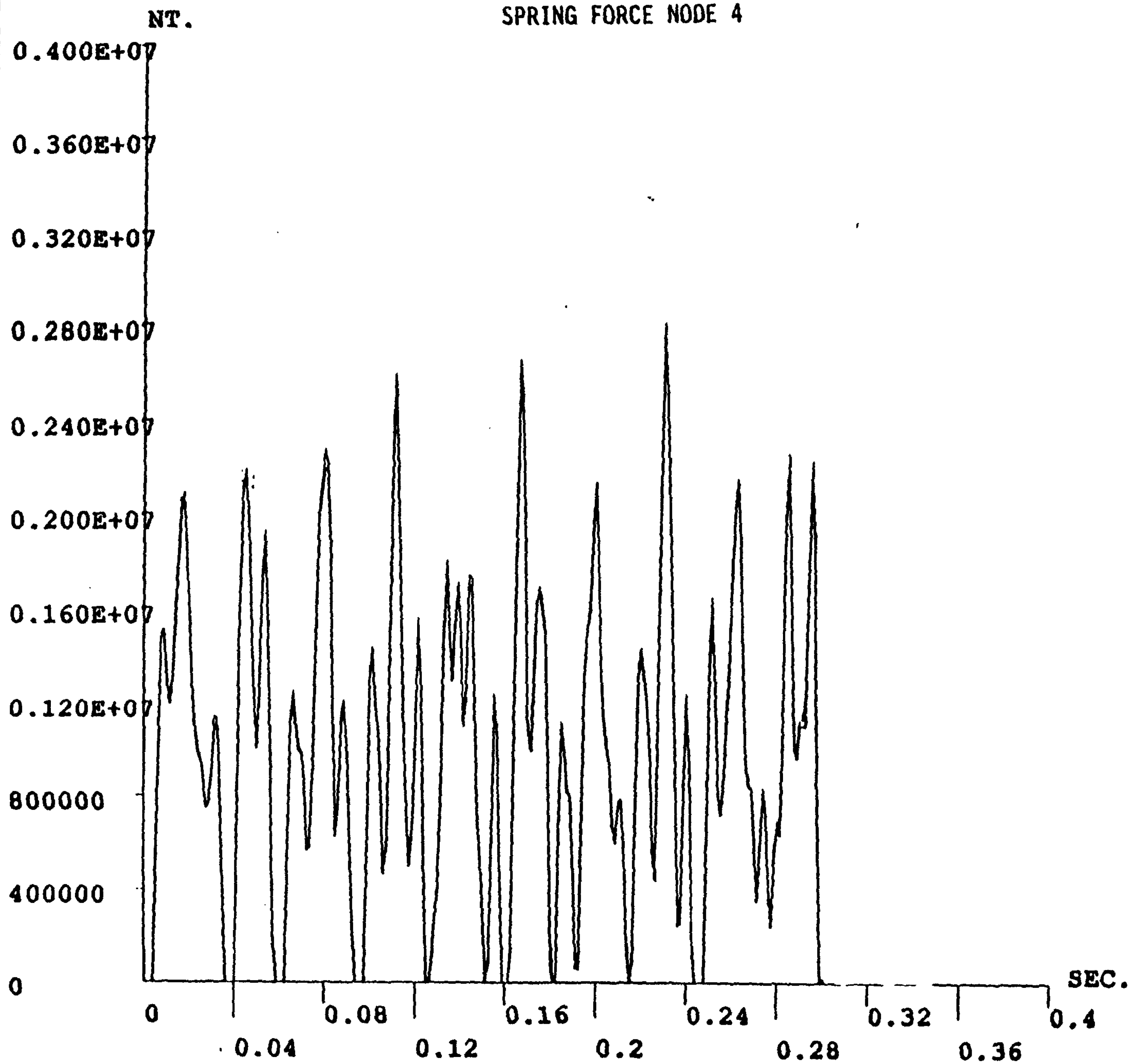
APPLIED FORCING FUNCTIONS

FIGURE 18

1

FIGURE 19

SPRING FORCE NODE 4



ANSYS
SEP 30
14:35:
PLOT N
POST26

ZV =1
DIST=0
XF =0
YF =0
ZF =0

FIGURE 20

SPRING FORCE NODE 6

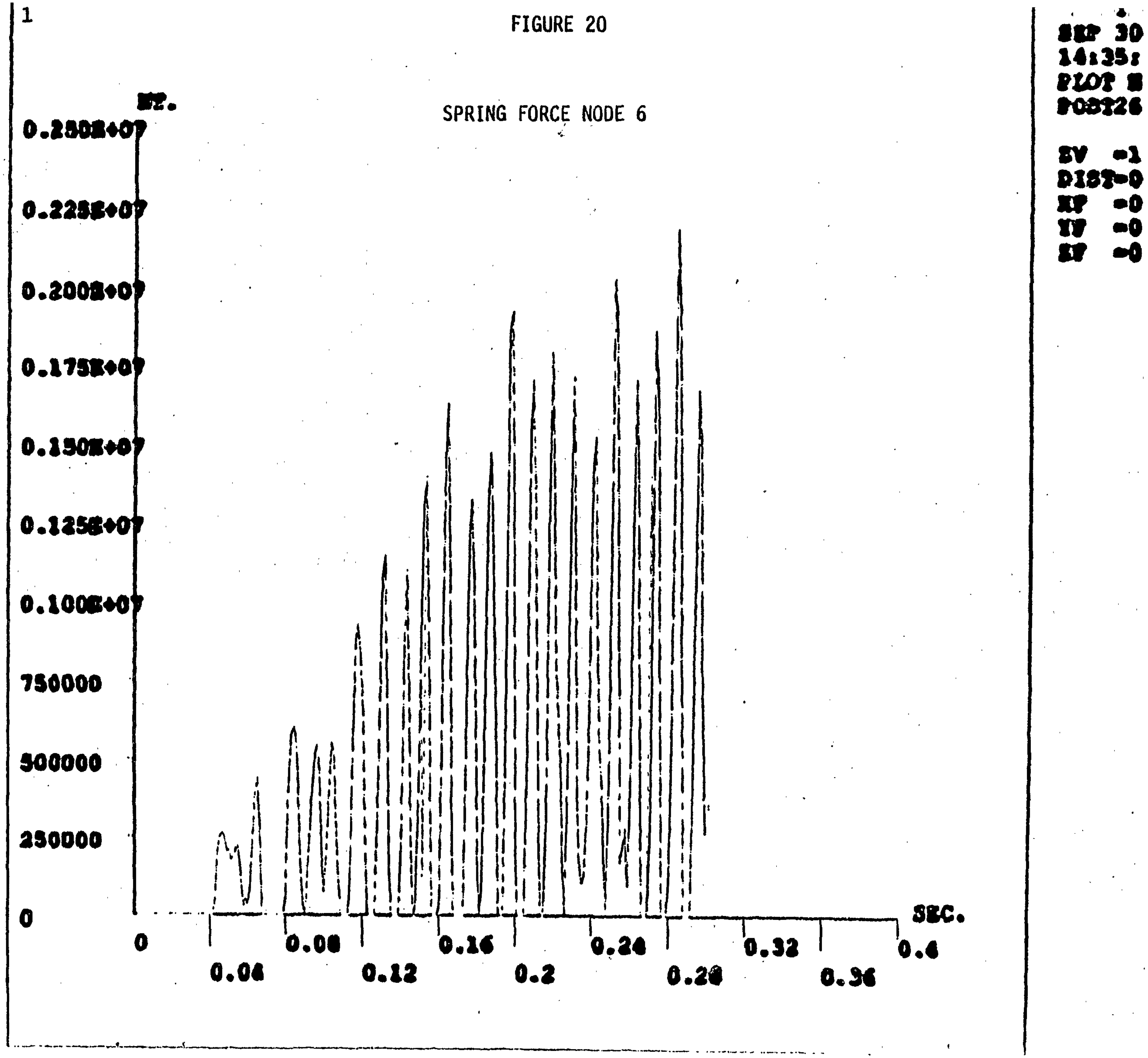
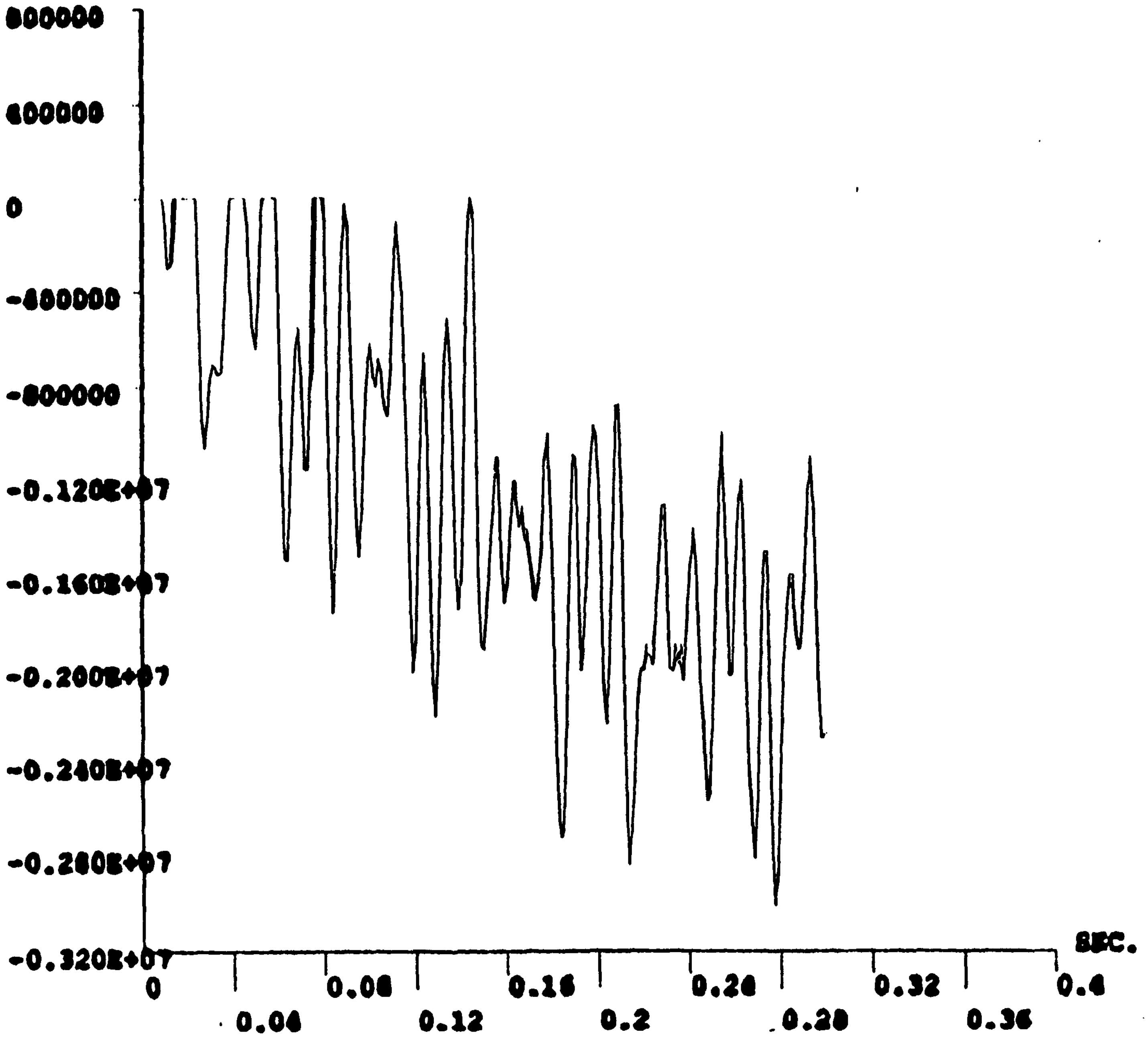
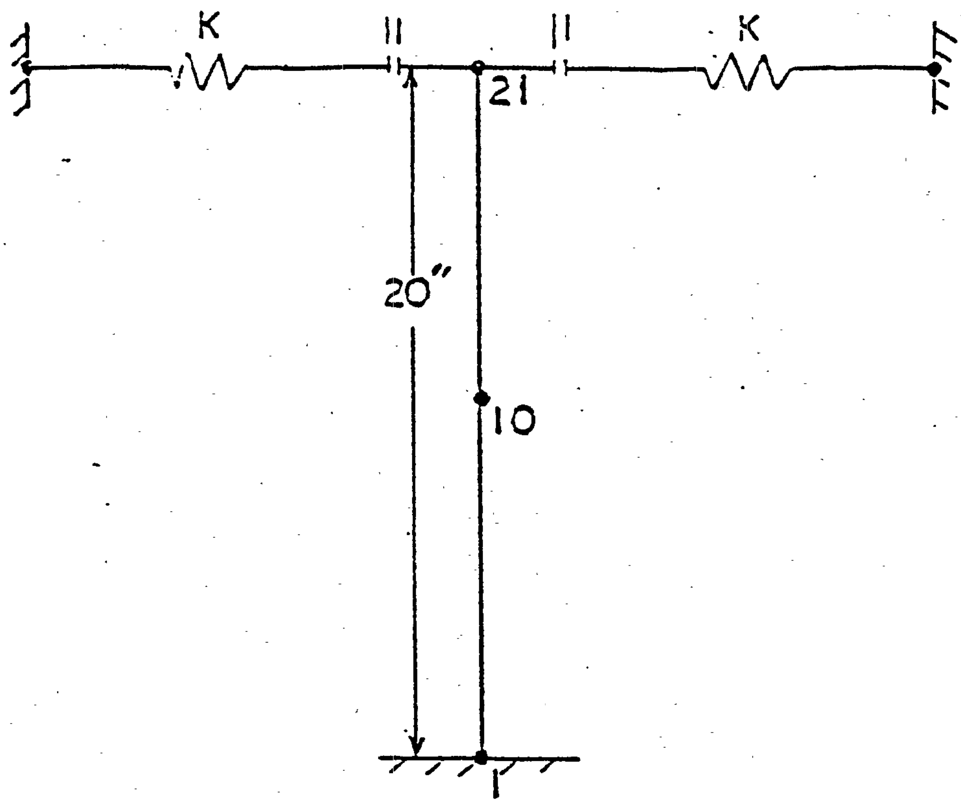


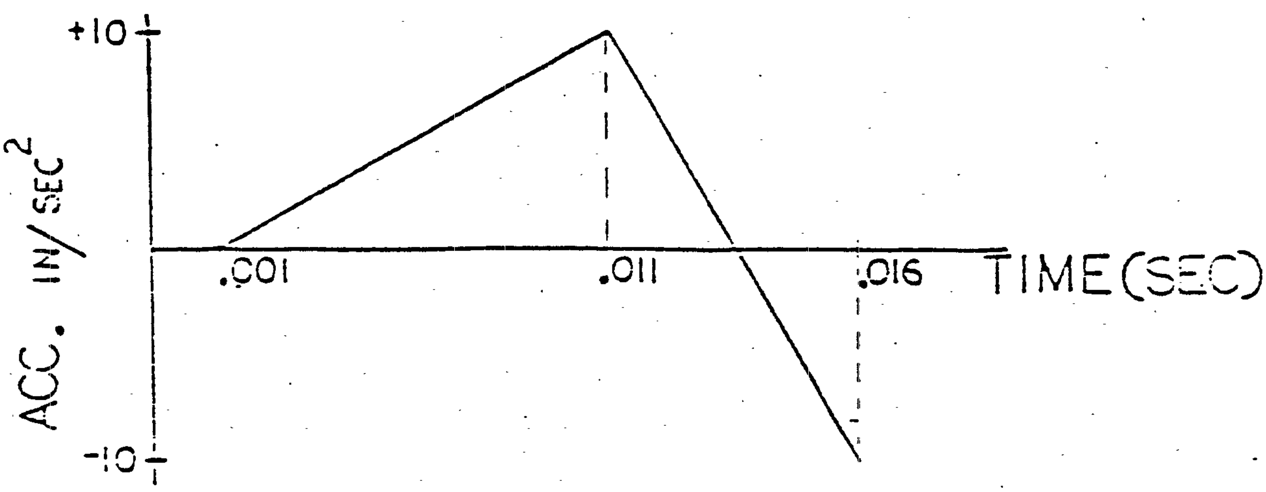
FIGURE 21

SPRING FORCE NODE 10





A. THE CANTILEVER BEAM MODEL



B. GROUND ACCELERATION

FIGURE 22 (A & B)

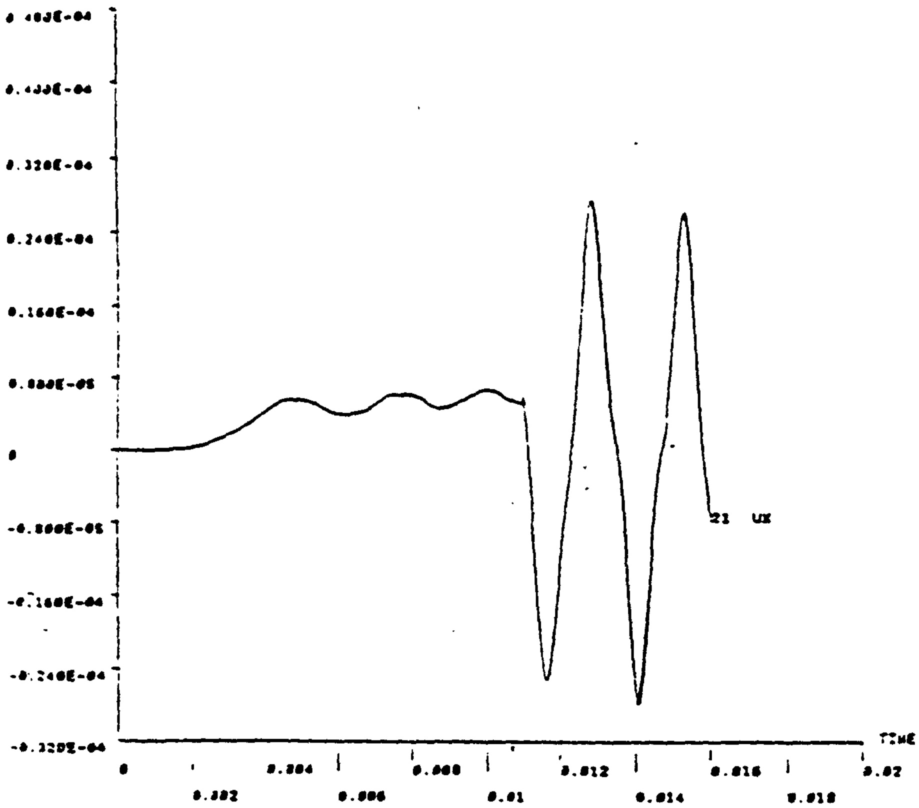


FIGURE 23A, DISPLACEMENT TIME HISTORY, ACCELERATION INPUT

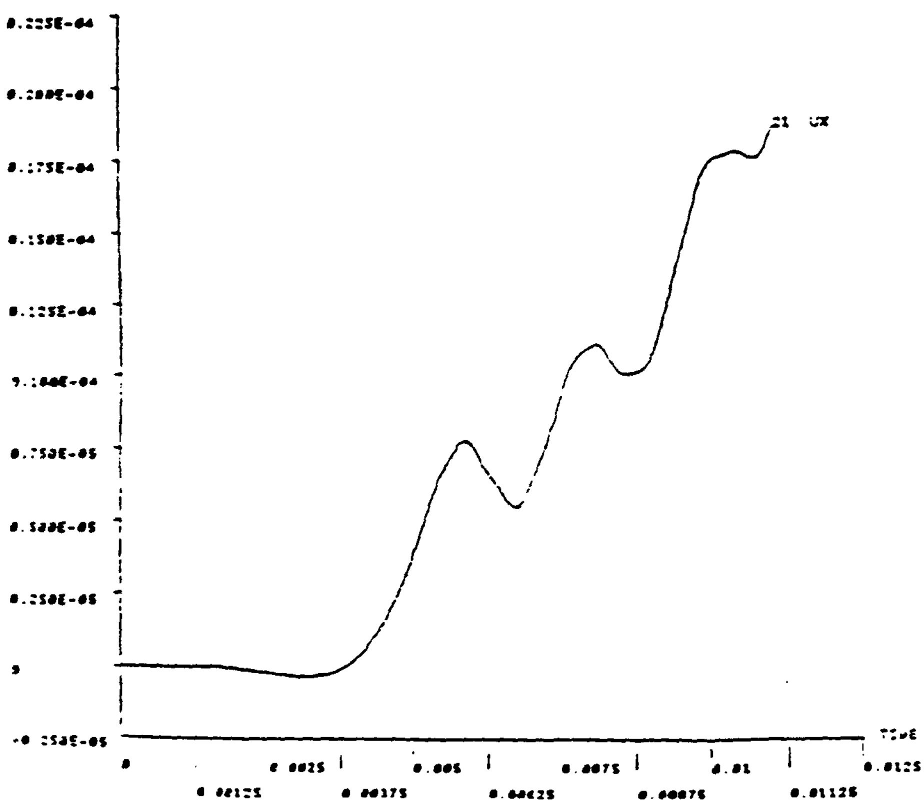


FIGURE 23B, DISPLACEMENT TIME HISTORY, FORCE INPUT

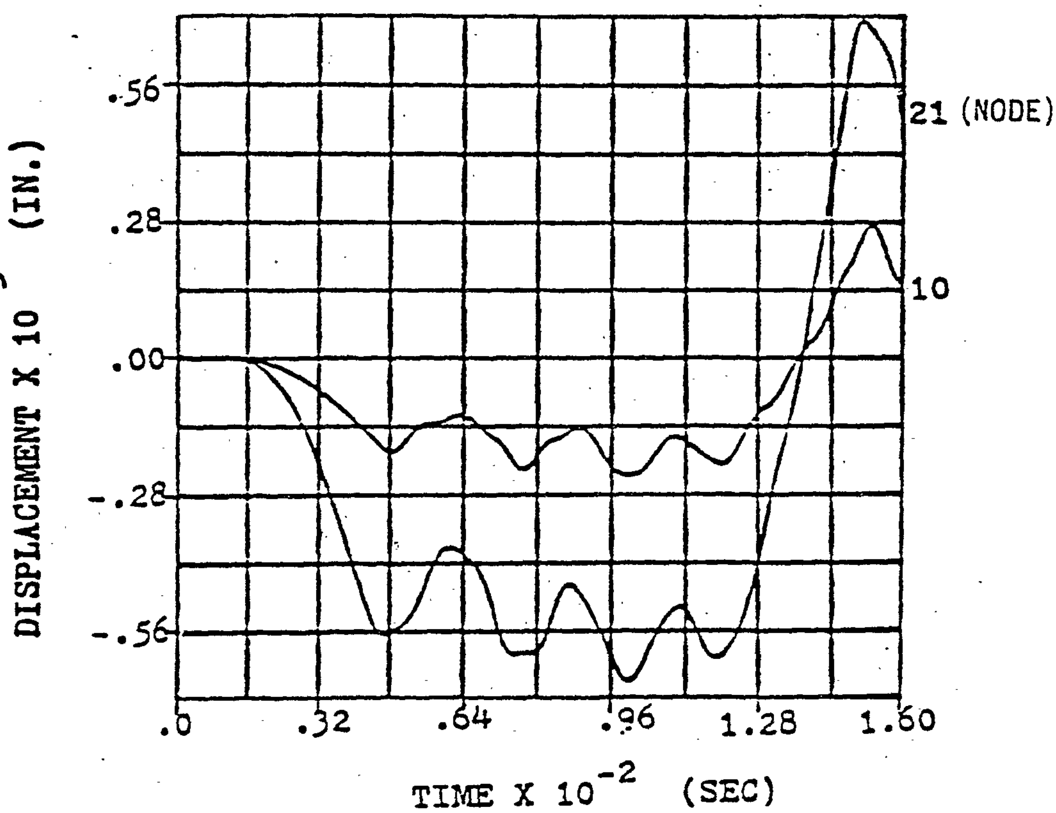


FIGURE 24 - DISPLACEMENT TIME HISTORY
PSEUDO FORCE ANALYSIS

APPENDIX A

PACKAGES OF INFORMATION PROVIDED
FOR STAFF REVIEW
OF COMPUTER PROGRAM - GAPPIPE

A. GAPPIPE User Manual and instruction for using GAPPIPE on the RLCA VAX Computer system.

B. CECO Piping Application Calculation Package, including piping description, model data, and GAPPIPE input/output listings (RLCA Calc. No. P182-1/02 Rev. A).

C. HDR SHAG post-test analysis data files and calculation reports on the comparison of GAPPIPE analysis results with test data for both Seismic Stop and Snubber support configurations.

D. Preliminary HDR-SHAM post-test calculation reports. (RLCA Calc. No. P101-10/21 Draft).

E. Copy of SHAM post-test technical paper by C. Kot, et al, at the 16th Water Reactor Safety Meeting (taken from NUREG/CP-0097).

F. RLCA calculation report on the implementation of Nonlinear Time History Analysis using the Pseudo-force Method in GAPPIPE (RLCA Calc. No. P94-4/35).

G. ANSYS model data and analysis comparison with the 1985 RLCA/EPRI Shake Table Tests.

H. Data plots of snubber and Seismic Stop responses from the 1988 RLCA/EPRI Shake Table Piping System Tests.

I. Input/output printout and plots of GAPPIPE analysis of sample piping systems illustration solution convergence and gap behavior.

J. Copy of ASME/PVP paper on the Pilot Study of Seismic Stop Pipe Supports at Millstone Unit 3.