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VERIFICATION OF EXPERIMENTAL MODAL MODELING USING HDR (HEISSDAMPFREAKTOR) DYNAMIC TEST DATA

by

M. G. Srinivasan, C. A. Kot, B. J. Hsieh,
J. A. Dusing, and E. L. Peterson

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ABSTRACT

VERIFICATION OF EXPERIMENTAL MODAL MODELING USING
HDR (HEISSDAMPFREAKTOR) DYNAMIC TEST DATA

by

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An attempt to verify the reliability of the experimental modal modeling code, MODAL-PLUS, is described in this report. MODAL-PLUS is capable of synthesizing a modal model of a structure using data from dynamic testing of a structure. The objective was to determine whether a modal model synthesized from one set of test data would be capable of correctly predicting response to a different form of excitation from a different set of data. Recorded test data from the shaker and rocket tests on the containment building of the HDR (Heissdampfreaktor) were used in the effort. The attempted verification was only partially successful in that only one modal model with a limited range of validity could be synthesized from the shaker test data. The goodness of fit in this limited range was adequate. The rocket test data could not be used to synthesize a modal model due to numerical difficulties. However, the effort was useful in showing the need for taking into account the possible use of the data, and the data analysis method to be employed, at an early stage when the tests are being designed.

FIN NO.	Title
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PREFACE

This report presents the results of an investigation conducted for the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES), Division of Engineering Technology. The work of developing and verifying modal models using experimental data was performed by the Structural Dynamics Research Corporation (SDRC) of Milford, Ohio under sponsorship of the Argonne National National Laboratory (ANL). Evaluation and interpretation of their findings was carried out by the staff of the Components Technology Division of ANL. The work was performed under a Standard Order for DOE work (FIN No. A2217). The project Monitor was Dr. J. F. Costello, NRC/RES; his helpful suggestions and reviews are gratefully acknowledged. The authors also wish to thank the staff of the PHDR Project at the Kernforschungszentrum Karlsruhe (KfK) in the Federal Republic of Germany for providing the experimental data necessary to carry out this effort.

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EXECUTIVE SUMMARY

Experimental modal modeling involves determining the modal parameters of the model of a structure using recorded input (excitation)-output (response) data from dynamic tests. Even though commercial modal analysis algorithms have been widely used for different kinds of structures, their ability to identify a set of reliable modal parameters of an as-built nuclear power plant structure has not been systematically verified.

This report describes the effort to verify MODAL-PLUS, a widely used modal analysis code, using the recorded data from the dynamic tests performed on the reactor building of the Heissdampfreaktor (HDR), situated in Kahl am Main, Federal Republic of Germany. In the series of dynamic tests on HDR in 1979, the reactor building was subjected to forced vibrations from different types and levels of dynamic excitations. Rotating eccentric mass shakers provided harmonic excitations at different force levels in one series of tests. Buried explosive charges, located near the reactor building, induced the vibrations in another series. In the third series of tests, the reactor building was excited by the reaction force from chemical rockets attached to the dome of the reactor building. In the tests, acceleration responses at different points of the building were recorded in digital form. The MODAL-PLUS code was developed by and is proprietary to the Structural Dynamics Research Corporation. Given the excitation force and response data, MODAL-PLUS determines the natural frequency, damping ratio, mode-shape vector, and modal mass for each mode of an assumed multi-degree-of-freedom model. The number of modes included in the model depends on the frequency content of the test data. MODAL-PLUS performs the modal extraction throug' curve fitting in the frequency domain. The code includes two single-degree-of-freedom and two multiple-degree-of-freedom (MDOF) techniques for obtaining modal parameters. In the present case, the MDOF techniques are used for obtaining the parameters.

Two sets of input-output data were chosen for MODAL-PLUS analysis. So that nonlinear behavior would not influence the results, the levels of excitation in all the sets are relatively low. Since excitation point response was not recorded in the HDR tests, and since the actual excitation was not truly a single-point excitation in the case of the shaker tests, certain assumptions had to be made.

The attempted verification was only partially successful in that only one modal model, with a limited range of validity, could be synthesized and the goodness of fit could be verified only in this limited range. However, two important conclusions regarding the planning and data analysis of dynamic

tests emerged from this study. The first is that the capabilities and limitations of the post-test data analysis method for modal parameter extraction should be taken into account in planning the excitation and instrumentation for dynamic tests. Otherwise the data and the parameter extraction method may prove incompatible. The second is that there is a need to develop/validate codes capable of estimating model parameters of large civil engineering structures subjected to general dynamic excitations in tests.

1. INTRODUCTION

Dynamic testing of large civil engineering structures, including nuclear power-plant buildings, was recently reviewed by the authors [1,2]. These evaluative reviews were performed to assist the USNRC (U. S. Nuclear Regulatory Commission) in establishing a basis for the structural analysis methods currently used in the licensing process.

One of the important findings of the reviews was that in most cases of dynamic testing of as-built structures, the purpose was to verify the analytical model of the structure through a comparison of modal parameters estimated from test data with those determined by pre-test or blind analytical modeling. Usually the modal parameters used in the comparisons were a few lower-mode natural frequencies, mode shapes, and damping values. The assumption implicit in this verification process is that the test-determined modal parameters are valid and thus provide the basis for the comparison. This assumption would be acceptable if the test was performed properly (i.e., all the desired modes were excited and appropriate measurements were made) and the procedure for estimating the modal parameters was correct. But in most cases of actual testing, although the test (excitation, measurement, etc.) generally was performed properly, the correctness of the parameter estimation procedure was not always clearly demonstrated. Since it was almost universally assumed that the structure behaves linearly (i.e., its modal parameters are constants), and since general principles of modal analysis are well established, the correctness of the estimation procedures was more or less taken for granted, as these procedures are based on the well established principles of modal analysis. Even though the wide scatter generally observed in the damping values determined from test data might challenge this attitude, the usual consistency in the values determined for modal frequencies and mode shapes provided assurance that the parameter estimation procedures were generally satisfactory.

In the literature surveyed on dynamic testing of structures, there is no report of any attempt to synthesize a modal model (capable of response prediction) from the test excitation response data. Yet the full potential of dynamic testing of as-built structures will be realized only when reliable mathematical models of structural dynamic behavior can be identified from test data. The authors also performed - as part of the same program on dynamic testing - an evaluative review of system-identification methodologies and applications [3]. This evaluation showed that the parameter estimation techniques applicable to linear structural systems must be systematically verified before they can be used with confidence to identify even linear (or modal) models of the structures tested. The work reported here grew out of this perceived need for verification of modal parameter estimation techniques.

The approach in this effort was to select a specific, widely available experimental modal modeling methodology and verify the reliability of the methodology in a systematic way. The proposed verification procedure was based on the idea that if a modal model synthesized from one set of actual test data from an as-built structure, say Set A, can predict with satisfactory accuracy the response of the same structure to a different excitation, say Set B of the test data, then the methodology that identified the modal model is verified. This procedure requires that actual test data - including data from different types of excitations - on an as-built structure be used. This requirement was readily satisfied by the availability of data from the Phase 1 tests on the HDR (Heissdampfreaktor) containment building. Thus it appeared it would be possible to implement this systematic approach to verification. In the following chapters of this report, details are given of the code selected for verification, the HDR tests and the data used in the verification effort, and the results of the effort.

2. EXPERIMENTAL MODAL MODELING AND "MODAL-PLUS" CODE

It is well known that the dynamic response of a structure, assumed to be linear in behavior, can be obtained by the superposition of the modal contributions. In the case of actual structures such as nuclear power plant buildings, it is common to assume that the response to dynamic loading may be well approximated by the superposition of a number of lower modes. Thus a structure might be mathematically represented by a system of a finite number of uncoupled ordinary differential equations, with each equation representing one mode. Such a mathematical representation is denoted a modal model in this report.

A modal model for a structure whose spatial configuration and material properties are known (or assumed) can be mathematically derived. An alternative method of obtaining a modal model for an existing structure is to synthesize one through dynamic testing. In this method the structure is subjected to a known dynamic excitation and its response is measured. A modal model is synthesized solely or partially on the basis of this input-output (excitation-response) data. A model so synthesized reflects the behavior of the real physical structure and so is likely to better represent the as-built structure than one derived solely on the basis of an analytical description of the configuration and material properties. However, the validity of a test-based model depends on the technique applied for determining it from the test input-output data. The techniques applied for synthesizing a modal model are of a class of parameter estimation methods. The basic assumptions of linearity and equivalent viscous damping is common to all the widely used parameter estimation or experimental modal analysis techniques. In addition to these, other assumptions based on experience and judgment may also be made by the analyst. The validity of the synthesized modal model depends on these, also.

As noted in the Introduction, in almost all cases of dynamic testing of large civil engineering structures, the modal parameters estimated from test data were one or more of the following parameters for each of a few lower modes: natural frequency, damping ratio, and the mode-shape vector. Synthesizing a modal model requires an additional parameter to represent the modal mass. If the excitation is in the form of known base motion, as in earthquake data, this parameter may be an effective participation factor [4]. Few have attempted to synthesize a modal model through the analysis of test data from any as-built civil-engineering structure. (Even the few attempts on the identification of linear models from earthquake data such as the one reported in Ref. 4 were in the realm of academic research rather than in the course of routine civil engineering practice.) This is in contrast with the increasing use of experimental modal modeling of mechanical systems for application in other industries such as aerospace, automotive, etc. The question addressed here is whether the commercially available experimental modal modeling methods commonly in use in such industries would yield accurate modal models (i.e., models capable of accurately predicting response to arbitrarily specified excitations) when applied to test data from real, large civil engineering structures.

MODAL-PLUS, a modal modeling algorithm developed by and proprietary to Structural Dynamics Research Corporation (SDRC), was selected as the candidate for verification because this code is one of the most widely used modal analysis tools in many industries. The theoretical basis of MODAL-PLUS is given in the User Manual [5]. A brief summary of this basis is given below. For an N-degree-of-freedom system with viscous damping, the frequency response function H_{ik} (i.e., the ratio of displacement at point i to the force applied at point k) is given by

$$H_{ik}(\omega) = \sum_{r=1}^{N} \{ \frac{A_{ik}^{r}}{\zeta_r \omega_r + j[\omega - \omega_r \sqrt{1 \ \zeta_r^2}\ ]} + \frac{A_{ik}^{r*}}{\zeta\omega_r + j\ [\omega + \omega_r \sqrt{1 - \zeta_r^2}\ ]} \} , \tag{1}$$

where ω is the frequency,

j is the complex notation for $\sqrt{-1}$,

ω_r is the undamped natural frequency of the r^{th} mode,

and ζ_r is the equivalent viscous damping ratio of the r^{th} mode.

A_{ik}^{r} and its complex conjugate A_{ik}^{r*} are the residues, and are defined by

$$A_{ik}^{r} = \frac{\psi_i^r \ \psi_k^r}{a_r} , \tag{2}$$

where ψ_i^r is the complex mode shape coefficient of the r^{th} mode at point i,

ψ_k^r is the complex mode shape coefficient of the r^{th} mode at point k,

and a_r is a complex constant for the r^{th} mode which depends on the r^{th} mode mode-shape vector, the mass matrix, and the damping matrix.

The inverse Fourier transform of Eq. 1 gives the unit impulse response function as

$$H_{ik}(t) = 2 \sum_{r=1}^{N} |A_{ik}^{r}| e^{-\omega_r \zeta_r t} \cos\{\omega_r \sqrt{1 - \zeta_r^2}\ t + \phi_{ik}^{r}\} , \tag{3}$$

where ϕ_{ik}^{r} is the argument of A_{ik}^{r} .

To synthesize the modal equation for the r^{th} mode, the parameters to be extracted from measured $H_{ik}(\omega)$ or $H_{ik}(t)$ are ω_r, ζ_r:

ψ_i^r, (i = 1, ... N), and

A_{ik}^{r} (i = 1, ... N, k = 1, ... N).

The residue A_{ik}^{r} can be shown to be related to modal mass and stiffness for a normal (i.e., real) mode model. Four extraction techniques are available within MODAL-PLUS. Two are single-degree-of-freedom techniques, treating each mode separately and providing only mode-shape coefficient data. Two others are multiple-degree-of-freedom (MDOF) methods, treating many modes simultaneously and providing all the modal parameters. The MDOF methods were the ones evoked in the present application. Both methods are based on the complex exponential technique, i.e., they fit measured impulse response to $H_{ik}(t)$ given in Eq. 3, using Prony's method [3] of parameter estimation. Although one of the methods uses single frequency response functions to estimate modal parameters, the other uses a set of frequency response functions to obtain better global parameter estimation. The latter involves a least-square-error implementation of the complex exponential technique, which is described in Ref. 5. Since for a real structure, N, the optimal number of modes to be included in the model is also a parameter to be determined from the test data, the least-square-error for different values of N is calculated and its variation with N is studied. A fit with fewer modes than really reflected by the test data will cause a large error due to the systematic error of not fitting all the resonances; a fit with more modes will give an error due to the noise in the measurement. When fitting with an increasing number of values for N, the error will stabilize for some value of N, reflecting the noise level in the data. Therefore, as one increases N, the optimal value for it is assumed to be achieved at the point where the error stabilizes and cannot be reduced further.

MODAL-PLUS also has a sort of built-in procedure for validating estimated model parameters. This procedure involves the synthesis of frequency response functions on the basis of the estimated parameters and is also explained in [5]. A synthesized frequency response function is compared with the corresponding experimentally acquired function to obtain a measure of the accuracy of fit. The validation procedure is more rigorous if the synthesized function was not among those used in the parameter extraction procedure. (In this context, the error in synthesizing frequency response functions is reduced if A^r_{kk}, the residue of H_{kk}, the driving point frequency response function, is used [6]; and consequently the MODAL-PLUS algorithm required that the driving point response be supplied as part of the input to the code.)

The present verification effort, however, did not use this feature of MODAL-PLUS for validating the modal parameter estimation procedure. Since the intention here was to verify the modal model (derived from one set of test data) by having it predict response to a different excitation (from another set of test data), an algorithm that would use the synthesized modal model to predict response to specified excitation was needed. The code SABBA, also developed by and proprietary to SDRC, served this purpose. The SABBA user manual [7], describes this method for determining the response from the modal model extracted with MODAL-PLUS.

3. DYNAMIC TESTS OF THE HDR CONTAINMENT BUILDING

The HDR containment building (65 m tall and 22.4 m in diameter) consists of an outer reinforced concrete, cylindrical shell capped with a hemispherical dome, an inner steel cylindrical shell with domed top and bottom, an internal concrete structure that supports the reactor vessel, steam generator, etc., and a massive reinforced concrete foundation mat that supports all the above structures. Structurally, the outer concrete shell and the inner steel shell are connected only through the foundation mat--an annular space separates them for most of their height; but penetrations, piping, and some structural members interconnect them at a few points [8].

During 1979, dynamic tests on the HDR containment building were performed with three types of excitation, viz. steady state sinusoidal forcing, impulsive forcing and blast-induced ground motions [9,10].

In the steady-state shaker tests, two shakers (rotating eccentric mass type) were located on the operating floor of the reactor building (elevation 30.85 m). The shakers provided unidirectional sinusoidal force in one of the two horizontal orthogonal directions (i.e., x or z directions) in each run. There were 19 test runs and in 18 of them the two shakers were operated in phase, and in the remainder a sinusoidal torque in the horizontal x-z plane was applied through antiphase operation of the shaker system. The frequency of the shakers was varied in increments - not necessarily uniform - covering the range 0.5-18.5 Hz over the 19 test runs. The amplitude of the applied force (of the two shakers) ranged from about 10 kN in some test runs to a maximum of about 500 kN in others. Although the force amplitude depended nonlinearly on the frequency of excitation, it was possible to achieve a desired range of force level at any run over a certain frequency range by adjusting the eccentricity of the shakers.

The impulsive forces on the containment were applied by means of reaction rockets mounted on the hemispherical dome (at an elevation of 44.5 m). The rockets were mounted so that the reaction force would be normal to the dome at the point of application; this resulted in a force that had a vertical component equal to about one-third the horizontal (z-direction) component. There were four test runs, with the peak force levels being about 100 kN in one, 200 kN in two, and 400 kN in the remainder. The force pulse in each run was approximately a square pulse of about 0.5 s duration.

The blast tests generated ground motions through the explosion of small charges (2.5-5 kg) located at distances varying from about 27 m to 36 m from the center of the building and buried to a depth of about 8 m. Six test runs were made with the size or location of the explosives different in each run.

The force of excitation was known with the greatest confidence for the steady-state tests, since in this case the force was easily computed from the known eccentric mass and the precisely controlled frequency. The total impulsive force in each of the rocket tests was not measured directly. The force from one rocket was measured during two of the four test runs. Since the two measurements agreed very closely, the total force in each test run was assumed to have the same pulse shape as the above measurments and a magnitude proportional to the number of rockets used in the test. Since the excitation in the explosive tests was actually the induced ground motions, there was no force measurement in these tests.

The response of the building was measured with accelerometers mounted at 18 locations: five on the base mat (elevation: -11.0 m), five on the outer shell at different elevations/radial locations, and eight on the inner structure, including the steel shell. Since more than one component of motion was measured at some of these locations, 32 total measurement records were obtained from most of the tests. More detailed information on the excitation and measurement are given in Refs. 8, 9, and 10.

4. SELECTION OF DATA

The proposed verification procedure was based on the idea that if a modal model synthesized from one set of test input-output data, say Set A, can accurately predict the output (i.e., response) for a different input (i.e., excitation), say test data Set B, then MODAL-PLUS would stand verified for synthesizing modal models of the HDR building. The accuracy of prediction was to be assessed by comparing the model prediction with the output from test data Set B. To eliminate the effects of amplitude-dependent nonlinear behavior, the response amplitudes of the two Sets A and B would have to be in the same range. Further, since the MODAL-PLUS algorithm requires frequency response functions to be defined as the ratio of response to exciting force, the data from tests with buried explosions as the source of vibrations could not be used for modal model synthesis. (In principle, it is possible with other methods to identify a modal model from such data using measured base motion as the input excitation. However, such a modal model can predict response only to given base excitations, and not applied forces; see [4]).

Based on the above requirements, two sets of test data were selected. The first set, denoted here for convenience as Set A, consisted of 32 response measurements from one series of shaker tests covering the frequency range 0.5-18.3 Hz. Set A included three sequences of forcing in each of the two horizontal directions with the two shakers synchronized to act in phase, and one sequence of forcing that produced a torsional couple in the horizontal plane through the antiphase action of the two shakers. The output of Set A was in the form of complex frequency response, and the input force was computed from a knowledge of the shaker mass and its eccentricity for each sequence. The second set, denoted Set B, was the response and force data from one of the four rocket tests. In this case, two rockets applied an impulsive force on the spherical dome of the outer structure. The force applied from only one of the rockets was actually measured. Since the rocket force pulses are noted to have been repeatable, it was assumed that the force history from the unmeasured rocket was identical to the one measured. Altogether, 29 response records (acceleration histories) were available for this set. Tables 1 and 2 summarize Sets A and B.

MODAL-PLUS, like other commercial experimental modal analysis codes, requires certain specific inputs for modal model synthesis. However, since modal model synthesis using a particular computer code was not necessarily among the original objectives of the HDR tests, certain incompatibilities between the test data and MODAL-PLUS were noted. First of these was that while MODAL-PLUS is based on single-point excitation, the shaker tests involved a two-point excitation. (A later version of MODAL-PLUS has been developed to include multiple-point excitations, but this version was not ready at the time of this study.) To overcome this problem, the resultant force or couple of the two shakers were assumed to be applied at a single point midway between the two shaker locations. The second and perhaps a more serious problem encountered was the nonmeasurement of driving-point response in the tests in the face of the requirement of the driving-point response among the others by MODAL-PLUS. An examination of the lower-mode shapes obtained by others [9] indicated that it may be possible to approximately interpolate the response at the driving point from the measured response at locations nearest to the driving point. Although this would introduce some error, it was judged that the error in lower-mode parameter estimates would not be large. The third problem arose in connection with the rocket test data. Here the sampling interval for the

Table 1. Data Set A (Selected from Steady-State Tests)

1. Excitation

SHAKER LOCATION (in HDR Global Coordinater)
x = -0.325 m, y = 30.85 m, z = -0.075 m

HDR Test ID	Direction of Shaker Force	Shaker Eccentricity, Kg m	Frequency Range, Hz	Amplitude of Force/Torque (kN or kN m)
V63.1.1.01	z	2266	0.5-1.83	22-300
V63.1.1.02	z	451	1.0-6.0	18-641
V63.1.1.04	z	28.6	2.5-18.0	7-366
V63.1.1.05	x	28.6	2.5-18.3	7-378
V63.1.1.07	x	451	1.0-6.0	18-641
V63.1.1.08	x	2266	0.5-2.2	22-433
V63.1.1.18	z/-z	128	1.0-9.0	23-1893

2. Response

32 channels of acceleration data in the frequency domain are used. For each frequency increment, data are given by a pair of numbers as real and imaginary parts or amplitude and phase with respect to shaker force. As frequency increments are not uniformly spaced, data are interpolated to obtain values at equal frequency intervals for use by MODAL-PLUS.

Table 2. Data Set B (Selected from Rocket Tests*)

1. Excitation

- Point of Application (in Global HDR Coordinater)

$x = 0.0$ m, $y = 44.5$ m, $z = 10.46$ m

- Description of Force

Force vector $\vec{F}$ is the resultant of two rocket forces

Magnitude of $\vec{F}$ in kN is digitized with a sampling interval of 0.005 s

The direction of $\vec{F}$ is given by:

$$\cos(\vec{F}, x) = 0, \cos(\vec{F}, y) = -.35714, \cos(\vec{F}, z) = -0.93405$$

2. Response

29 channels of acceleration data in the time domain, with a constant sampling interval of 0.002 s, and a record length of 10 s.

*HDR Test ID: V65.3.2, no. of rockets: 2.

rocket force was two and a half times that for the responses. But MODAL-PLUS required that the time increments be the same for both. This made it necessary to interpolate additional points for the rocket force data. Further, since the force history and response histories had not been recorded with the same time reference, the two had to be manually synchronized. These two approximations were not expected to result in serious errors.

5. DISCUSSION OF RESULTS

The identification of the modal model of the HDR containment building was performed by the staff of SDRC. The results of this effort, as reported by SDRC, are given in the Appendix. The following is a discussion of the results of the verification effort.

A preliminary analysis of the shaker test data (Set A) was made to obtain approximate estimates of modal frequencies, damping, and mode shapes with the single-frequency-response function method of MODAL-PLUS. This analysis covered the frequency range 0.5-8.5 Hz. The results of the analysis, together with a comparison, are given in Table 3.

Eleven modes were approximately identified in this frequency range, but the analysis indicated that only the lowest four modes were unambiguously identifiable from the data. The fifth mode appeared to be predominantly one of outer structure vibration. This mode had been identified as a probable shell mode by German investigators [9]. This mode and the next two higher modes, all closely spaced, were shown by this preliminary analysis to be poorly excited. These modes seem to have significant torsional motions, but also could have been local modes. The eighth and ninth modes also were identified by MODAL-PLUS with some ambiguity. (The structural action of these modes had not been clearly identified by the German investigators, as they qualify these as "probable" [9].) Even though the tenth mode was clearly identified as a torsional mode, the eleventh mode was somewhat ambiguous. The occurrence of significant torsional motions around 5 Hz invalidated the assumptions that the two shaker forces could be approximated as single resultant force acting at the center of action of the two shaker forces and that the driving point frequency response functions may be obtained by interpolation. Therefore the modal model to be identified by MODAL-PLUS had to be limited to the first four modes only. Further since the damping ratios determined in the preliminary analysis were found to be small, it was assumed that the mode shapes may be considered to be "classical" normal modes, i.e., these are real-valued modes, rather than the

Table 3. Preliminary Parameter Estimates from MODAL-PLUS and Comparison with German (KfK) Estimates

Mode No.	Nat. Frequency, Hz		Damping, % Critical		Mode Description
	KfK Investigations	MODAL-PLUS	KfK Investigations	MODAL-PLUS	
1	1.48	1.48	5 4		Rocking, in phase, x
2	1.54	1.53	5.4	5	Rocking, in phase, z
3	2.47/2.59	2.53	3.5	4	Bending, out of phase, x
4	2.65/2.66	2.68	2.6	4	Bending, out of phase, z
5	5.00	5.05	3 6		Shell action, outer structure
6	5.7-5.9	5.23	Not available	6 (probable)	Torsion, in phase
6a	Not identified	5.34	– 6		Outer structure, z & torsion
7	6.32	6.43	3.4 (probable)	3	Local, outer structure, z
8	6.54	Not identified	4.2 (probable)	–	Bending, outer structure,x
8a	Not identified	6.72	– 2		Bending, out of phase, x
9	7.32	Not identified	2.3 (probable)	–	Local shell, outer structure, z
9a	Not identified	7.2	– 2		Torsion&outer structure,z
10	7.8	7.8	2.8	3	Torsion, out of phase
11	8.5	Not identified	1.4 (probable)	–	Local, outer structure, x
11a	Not identified	8.5	– 3		Torsion

complex-valued modes associated with the most general case of viscous damping.

Table 4 gives the natural frequency, damping ratio, and modal mass identified by MODAL-PLUS (using the multiple-frequency-response-function method) for the first four modes. The three-dimensional mode shapes were also given by MODAL-PLUS and are given in the Appendix. The mode shapes were normalized by taking the largest absolute shape coefficient to be unity, before calculating the modal mass.

The attempt to obtain a modal model from the rocket tests failed due to an inability to generate valid frequency response functions from the data. The frequency response function is obtained by dividing the Fourier transform of the response by that of the applied force. Typical frequency response functions computed showed (see Fig. 1, for example) too many peaks, at least some of which appeared to be spurious. This led to an examination of the Fourier transforms of the response and rocket force. Although the peaks in the transform of the response occurred at the known resonant frequencies, as seen from Fig. 2, the transform of the rocket force (Fig. 3) had many near-zero values at frequencies corresponding to the spurious peaks of the frequency response functions. The presence of these "valleys" is easily explained. The rocket force, in the time domain, is approximately a rectangular pulse of 0.5 s duration. This characteristic is reflected in the frequency domain by near-zero value of the transform at frequency values of 2 Hz, 4 Hz, 6 Hz,..., etc. Thus, this was essentially a numerical problem since theoretically the frequency response function depends only on the dynamic parameters and not on the applied force.

The lack of a second modal model (i.e., from Set B) and the limited frequency range of the first modal model from Set A made the original objective unattainable. However, as a sort of verification of the goodness of fit achieved in the modal model from the shaker test, this model was subjected to a simulated shaker test in the frequency range of 1-5 Hz--the range of validity of the model. The frequency response of this modal model to a unit force, in a steady-state sinusoidal test covering the frequency range 1-5 Hz, was computed with another code, SABBA, also developed by SDRC. A comparison of the computed response at a point on the internal structure (Fig. 4) with that obtained from the test (Fig. 5) shows that the MODAL-PLUS curve fitting was very good indeed.

Table 4. Model Parameters Estimated by MODAL-PLUS From Data Set A

Mode	Frequency, Hz	Modal Mass, kg	Damping, % of critical
1	1.48	20742	4.1
2	1.53	14381	4.7
3	2.54	6743	3.6
4	2.68	8160	3.8

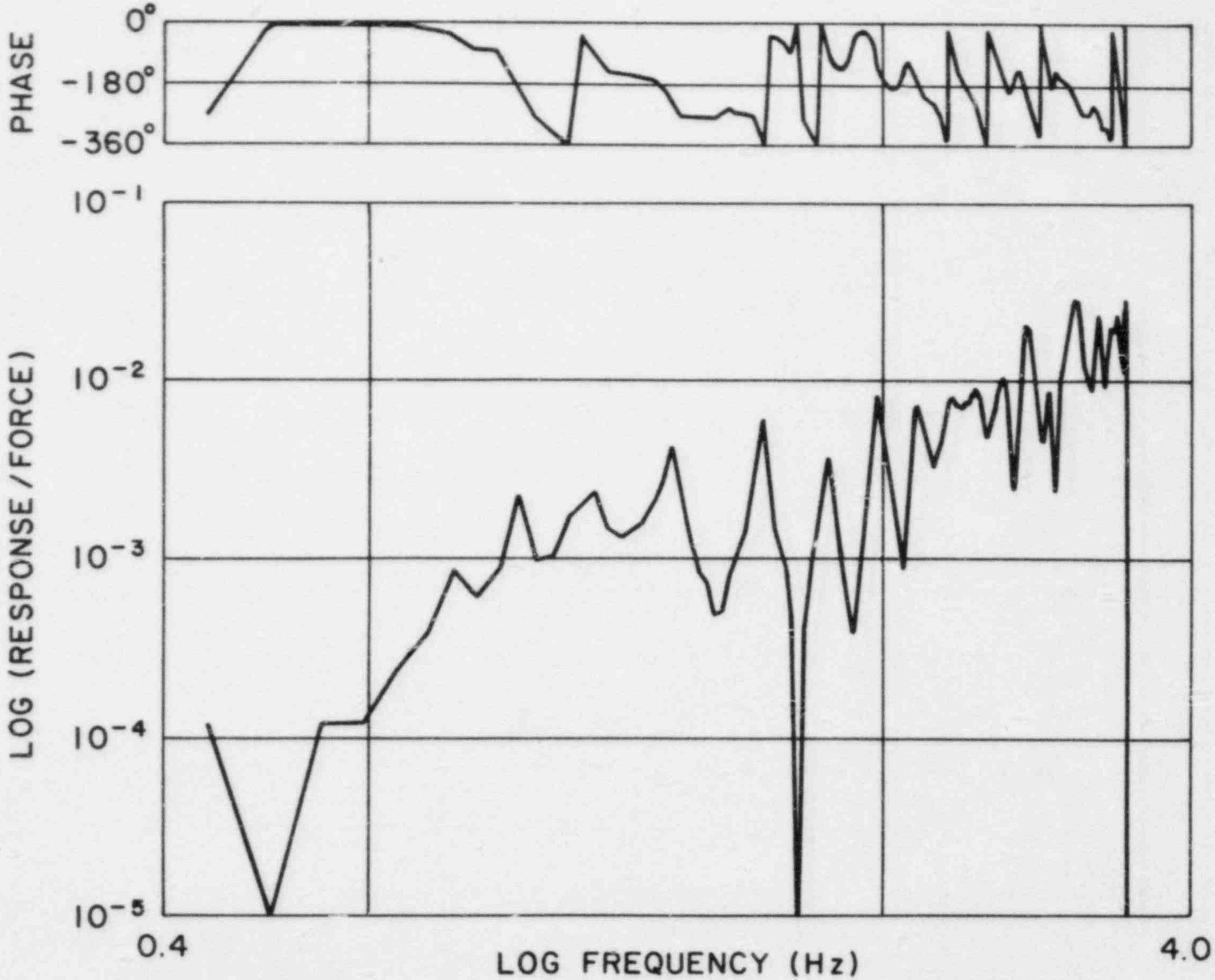

Fig. 1. FRF from Rocket Data (for response point 187Z)

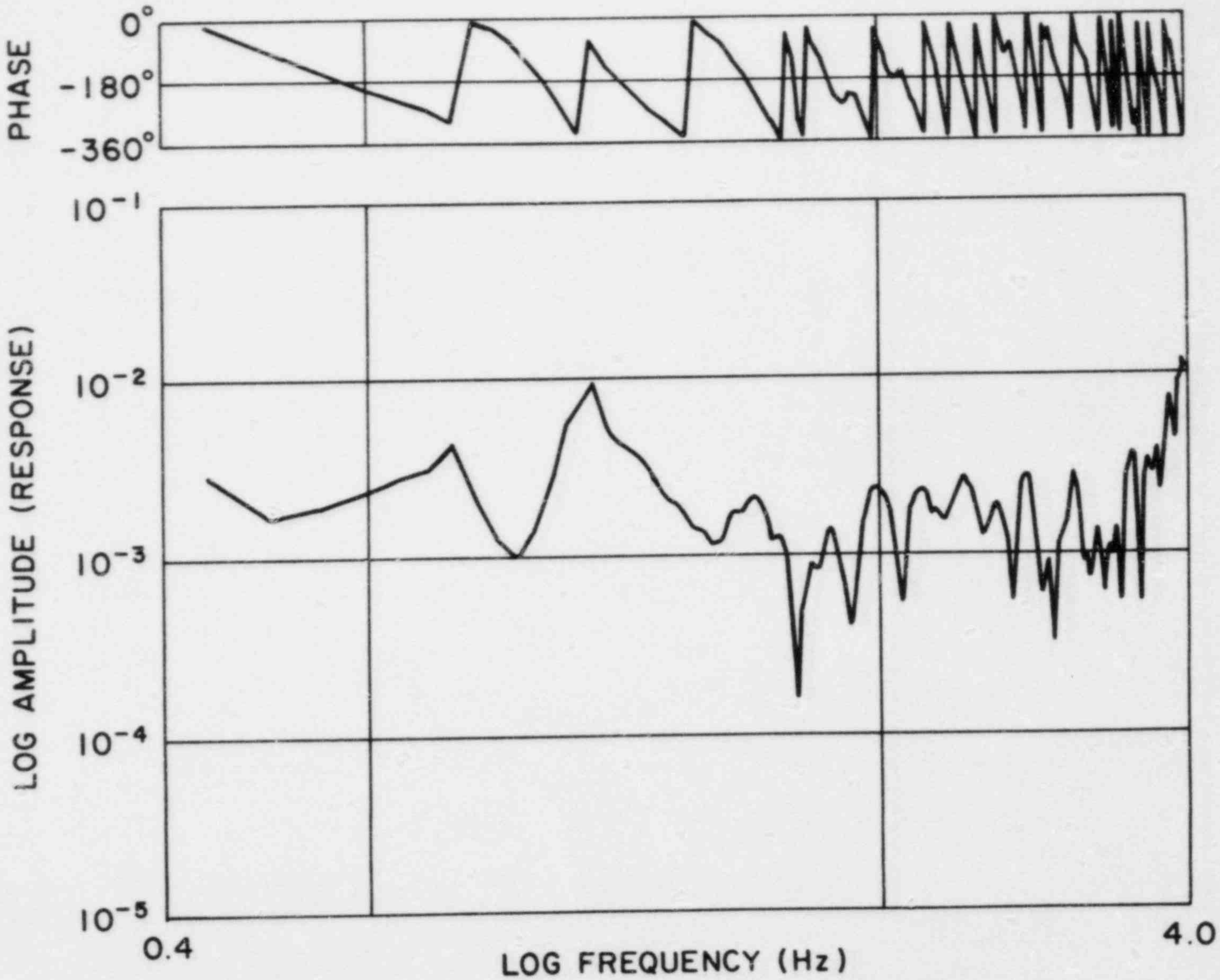

Fig. 2. Response Spectrum at Point 187Z Due to the Rocket Blast

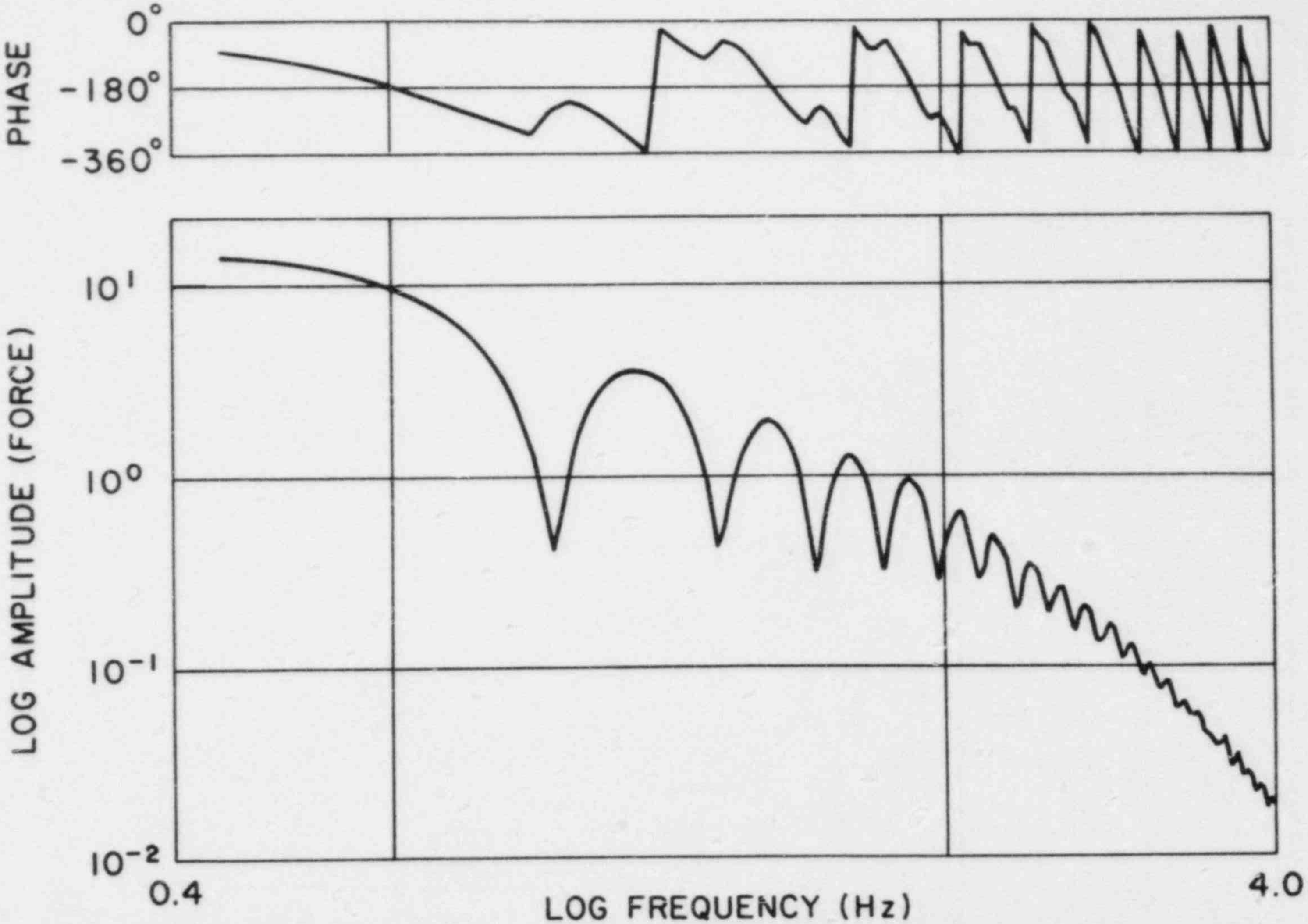

Fig. 3. Force Spectrum of the Rocket Input

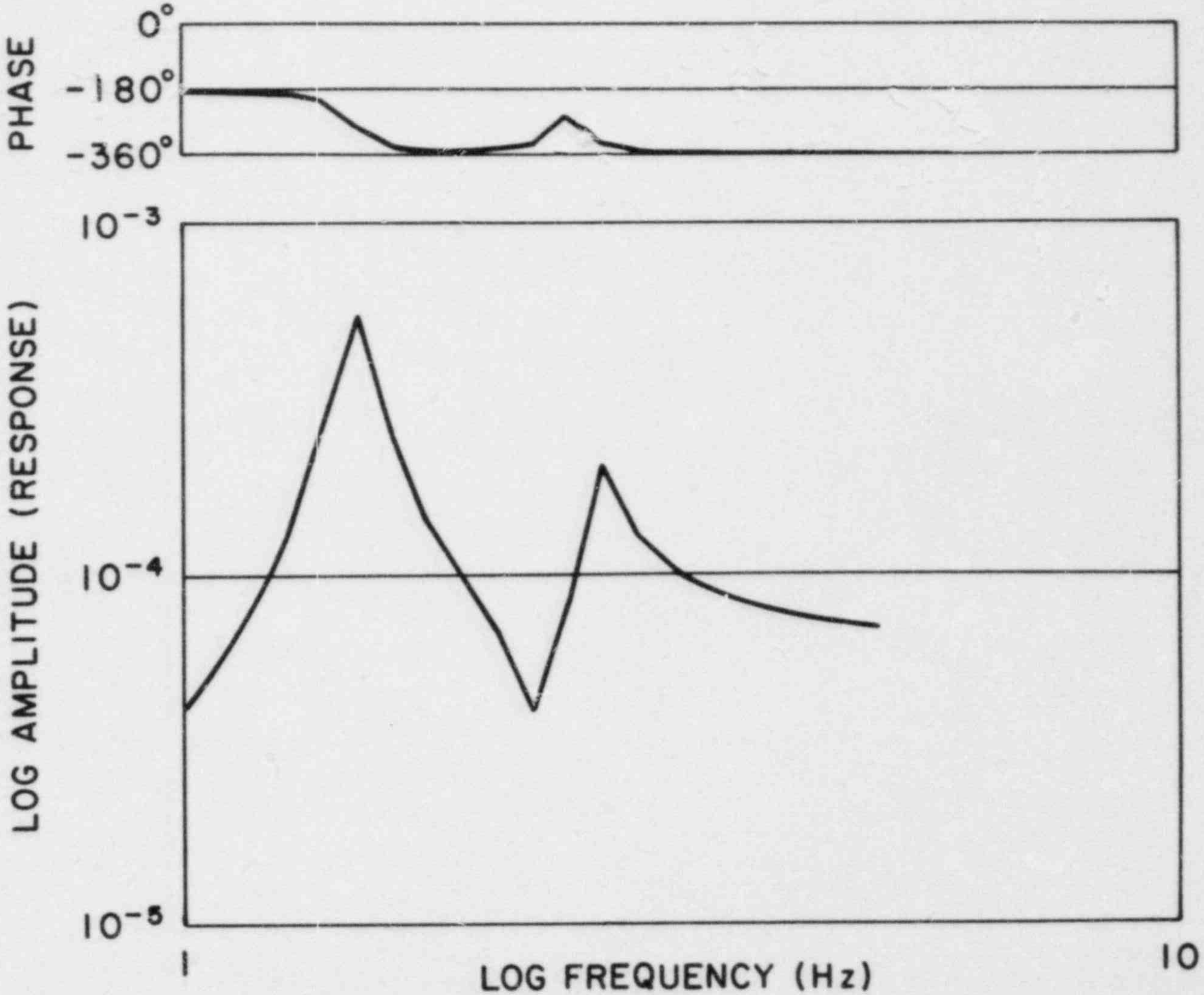

Fig. 4. Computed Response (acceleration in m/s^2) at 33X

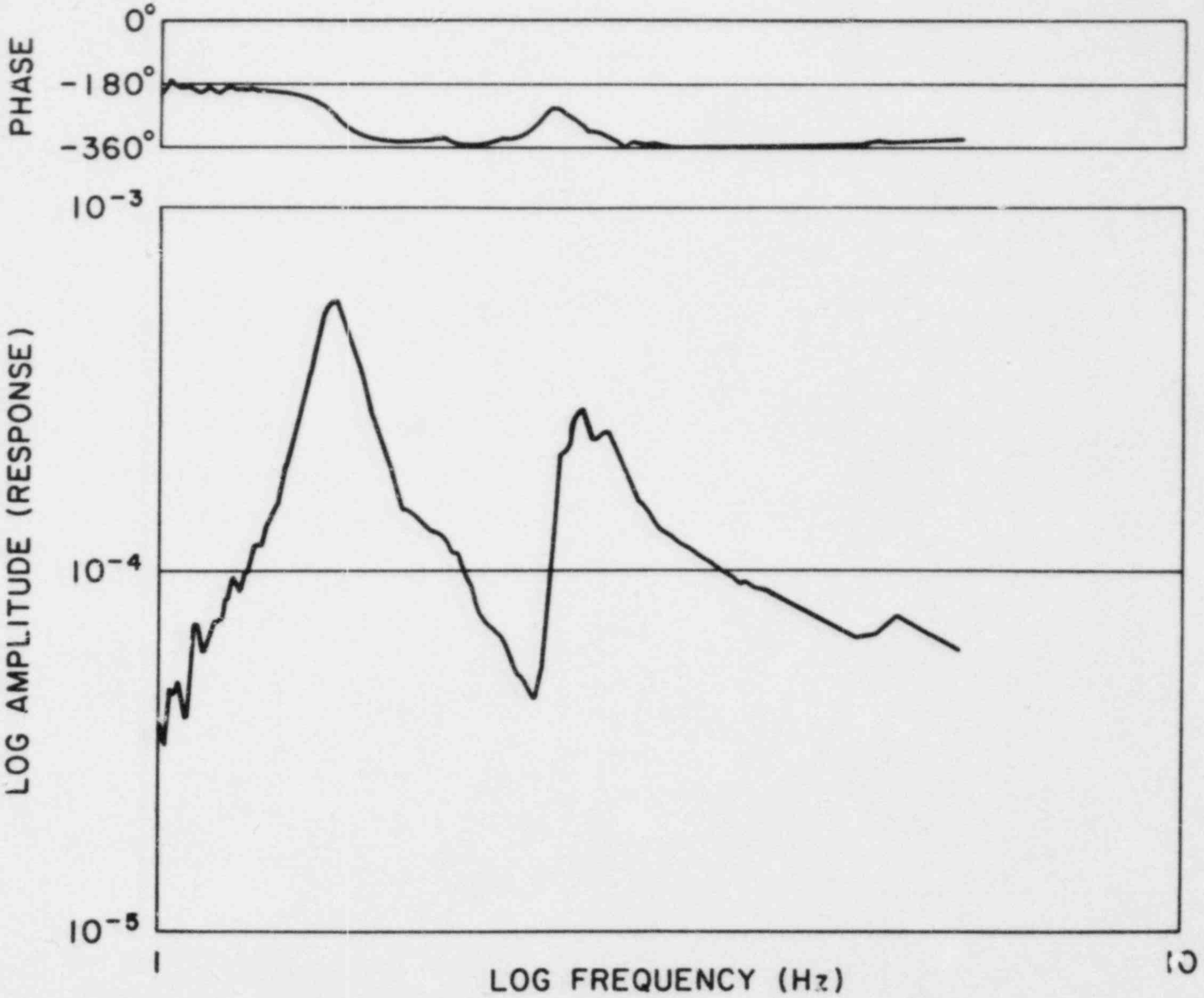

Fig. 5. Measured Response (acceleration in m/s^2) at 33X

6. CONCLUSIONS

Although the original objective of the effort could not be attained, mainly because of the incompatibilities between the data and the parameter estimation method, useful conclusions emerged from this study. In devising the test excitation and response measurements (i.e., number and location of measurements), the method of data anlysis and the expected results must be taken into account. For instance, if the goal of the test is to determine only the natural frequencies, damping ratios, and mode shapes, then it may not be necessary to accurately measure the forcing function but only to know certain frequency characteristics of the excitation. In contrast, if the test objective is to synthesize a modal model then it is necessary to measure the force as well as the response on the same synchronized time frame.

There is a need for the development of modal parameter extraction methods applicable to general dynamic testing situations involving large as-built structures. In almost all cases of dynamic testing of as-built civil engineering structures, the goal was to verify analytical modeling through a comparison of modal parameters estimated from the test with those given by analysis [2]. But the model verification was always partial since modal masses or participation factors were not usually estimated from test data. This may be because the methods available were not capable of estimating modal masses. Until parameter estimation methods capable of extracting a "complete" modal model from experimental data obtained from the most general dynamic testing conditions become available, it is necessary for test planners to recognize the capabilities and limitations of commercial available codes such as MODAL-PLUS. Devising tests on as-built structures that are compatible with such codes, and validating the codes through use of test data from real structures are the requirements for establishing the accuracy of modal models derived from test data.

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APPENDIX

SDRC Project No. 11340

MODAL ANALYSIS AND MODAL MODELING USING HDR TEST DATA

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I. EXECUTIVE SUMMARY

I.1 BACKGROUND

Dynamics tests were performed on the Hessdampfreaktor (HDR) reactor building (see Figure 1) in Karlshru, Germany in 1979 by a California based company called ANCO. Those tests involved the application of various mechanical input forces while measuring the resulting responses. The basic purpose was to study the structural characteristics of the building system (including presumably not only the structural steel and concrete of the building itself, but also the soil/structure interaction, the effects of attachments to the containment structure, the effects of non-linearities, etc.).

This data was stored on IBM formatted 9 track mag tape.

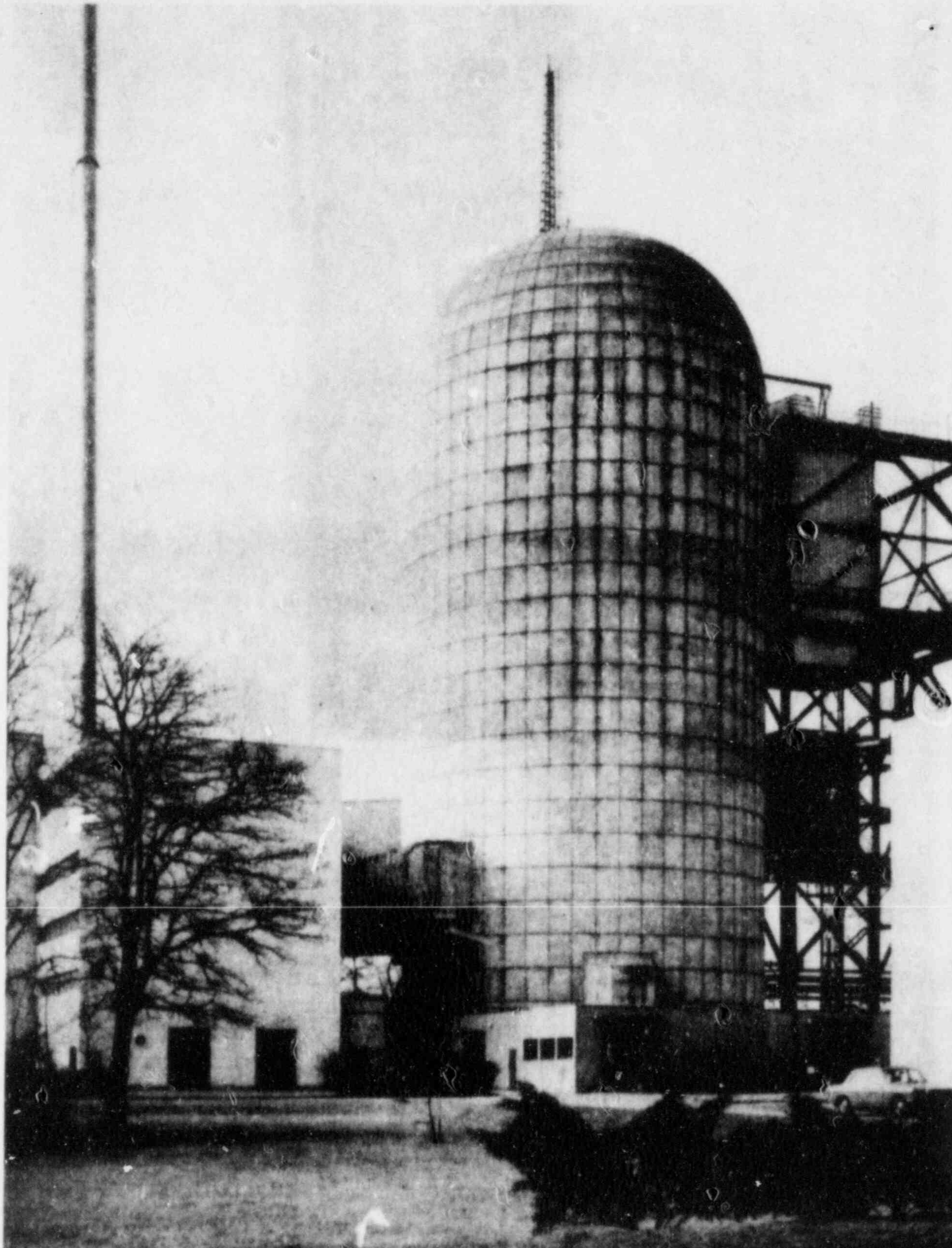


Figure 1

Karlshru/HDR Reactor Building

I.2 OBJECTIVES

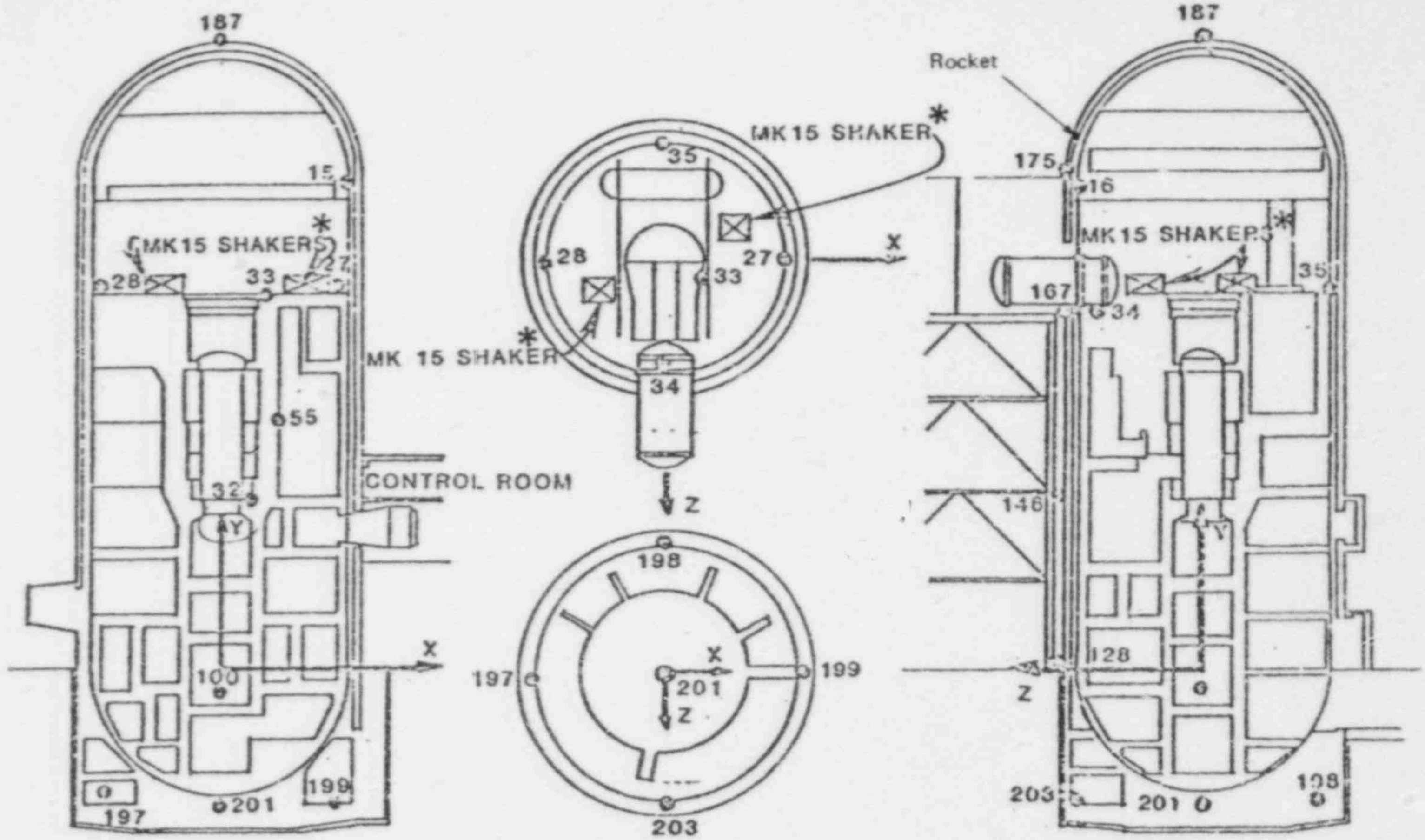
SDRC was asked to analyze certain portions of the Karlshru/HDR data, in particular the multipoint dual rotating mass shaker data, the rocket data, and the explosion data. The main objective was to find out if a complete and valid modal model of the system could be extracted from the Karlshru data.

Appendix A is the "Statement of Work" from the contract.

I.3 APPROACH

The basic plan was to get as complete a model as possible from each of the 3 types of tests for the geometry points obtained on site (see Figure 2), then to compare the models themselves and also compare the forces response predictions resulting from these models.

When appropriate test data are presented to MODAL-PLUS and SA3BA, they can produce a very valid model. Figure 3 shows the flow of this type of analysis. Obviously the output of one step cannot be any more reliable than the input so it is essential to start out with an appropriate test plan for any "model from test data" activity.



*When the two MK15 dual rotating mass exciters were "in-phase" with each other in the X direction the MODAL-PLUS reference coordinate code was labeled 533X. When the two shakers were in-phase with each other in the Z direction the reference coordinate was labeled 533Z. When the two shakers were out-of-phase with each other the reference coordinate was labeled 534.

Figure 2
Measurement Points

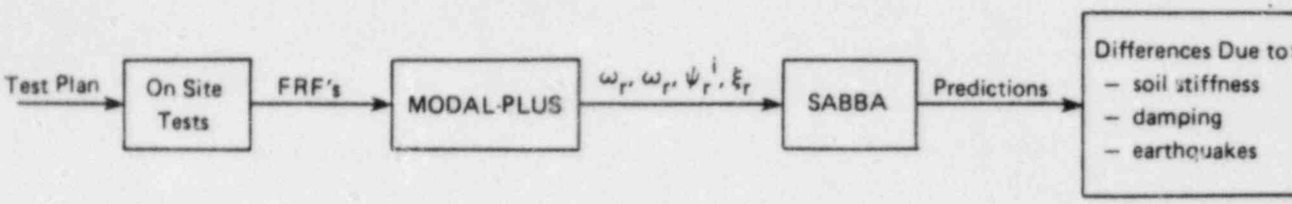


Figure 3
Modai Modeling Process

I.4 RESULTS

The HDR data which was collected in 1979 has many severe deficiencies from a modal modeling viewpoint. It is apparent that the data was collected for the sole purpose of identifying certain types of natural frequencies (i.e. the simplest modes) and the associated damping and mode shapes.

These deficiencies* prevented SDRC from developing a valid modal model of the structure (except for one very simple case which is probably of very limited value---it is, however, documented in Section II.4).

This limited modal model (from MODAL-PLUS) of the HDR structure was put into SABBA. This was done mostly as an instructive exercise to show the entire process.

* Documented in Section II.

I.5 RECOMMENDATIONS

1. It would not be cost effective to spend any more time or money trying to get a modal model from this test data. SDRC engineers expended far more than the proposed amount of time (using discretionary time) in a vain attempt to get viable results from this data. The basic nature of the data simply precludes its use in obtaining a usable modal model.

2. If it were desired to obtain a complete and valid modal model of the HDR building from some future test. SDRC would make the following recommendations:

   a. All currently available modal modeling techniques depend on the single point input approach.

      The multipoint input method can be used to get valid mode shapes, natural frequencies, and damping; it is not possible however, to get the modal mass (which acts as a scaling factor between modes) from multipoint input tests.

      The dual rotating mass exciters were unfortunately, a multipoint input. We had hoped that the building would have negligable torsional response out to 15 or 20 Hz (thereby allowing us to assume that the "in-phase" exciter* test had an equivalent input location located half way between the two exciters). Unfortunately, torsional characteristics began showing up as low as 7 to 8 Hz so the aforementioned simplication was only valid below 7 Hz for the shaker data.

   b. The force measurement is by far the most crutial in the entire set of transducers.

* See Figure 2

It is essential to get an accurate, valid measurement of the actual input that goes into the structure so that the FRF's* are valid.

The force data from the rocket tests was not valid data (as is documented in Section II.2). This prevented use of the rocket data in obtaining a modal model. The explosion force could not be measured so it was impossible to use the explosion data to develop a modal model.

c. The response location at the exciter (i.e. the driving point accelerometer) is the second most important measurement in the entire set of transducers. The driving point FRF plays a crutial role in determining the quality of the raw data, the validity of the modal model, and the ability of calculating modal mass (See appendices B and C).

Since there was no measurement made at the driving point for any of the tests, it was necessary to make the assumption that a response point close to the exciter was the same as would be obtained at the actual, exact driving point. This assumption turned out to be valid only up to about 7 Hz for the multi-shaker data since the system exhibited torsional characteristics in the 7-8 Hz range.

d. In order to calculate a modal mass with reasonable accuracy, it is essential that the mode in question be well excited by the exciter. This means that each natural frequency must stand out well in the driving point FRF.

In practice it is almost always impossible to get each one of the modes of interest of a system to be well excited by any one

* Frequency Response Functions (FRF's) are a special type of transfer function (i.e. a transfer function in the frequency domain is an FRF).

exciter location. In general several (often many) exciter locations are necessary in order to assure that each significant mode is well excited by at least one exciter location. The term "well excited" is, of course, very prone to judgement. One rule of thumb to use is that any mode that clearly stands out of a driving point FRF as a separate well defined peak will almost always yield a good modal mass for that mode; when a mode shows up as a small "blip" in the driving point FRF, it may be possible to get a reasonable mode shape of that mode from that exciter location, but it will be nearly impossible to get a valid modal mass (which is, of course, crutial to a modal model).

The end result is that it is often necessary to have 5, 10 or even 15 exciter locations on a complicated structure.

The dual rotating mass exciter showed some modes in the 5-6 Hz area (see Section II.1) that are very poorly excited. Neither the in phase nor the out of phase runs [1] brought these modes "out in the open." There was some activity noticed in the explosion response spectra and rocket response spectra. This presents the possibility that there are strong system modes which have high amplitudes at other locations of the system (e.g., the "truss type" structure connected to the containment building?). These modes, whatever they are, were poorly excited by the dual rotating mass exciters. The only way to tell what these modes [2] are would be to try many exciter locations (e.g., 20) and build up a total list of all of the natural frequencies up to some F_{max} along with a notation as to which exciter location(s) best excites each mode.

[1] See Figure 2.

[2] It is, of course, important to define them from the tests so that an informed decision can be made as to whether they're important (they may or may not be negligable in the total system).

If a response location is taken at each of the 20 exciter locations for each excitation run, then the resulting set of 400 FRF's can be used to check reciprocity (i.e. $H_{ij} = H_{ji}$). Since the only requirement for reciprocity is linearity, this also becomes a check on linearity.

SDRC would expect that a subset of perhaps 8 or 10 exciter locations could be selected that adequately excite all of the modes of interest. The finite element model(s) that evidently already exist should be a lot of help in picking the initial 20 exciter locations but great care must be exercised so as not to restrict the number of locations (otherwise the tests are guaranteed not to show any modes that the model(s) do not predict!!).

SDRC has extensive experience in field data acquisition for modal models so we certainly realize that it is an extremely difficult task to obtain so many exciter locations. To use a large rotating mass exciter may or may not be feasible. For this "exciter search" activity, however it is probably not necessary to have the large force levels of the rotating mass exciter. In fact, step relaxation may be able to do a reasonable job of locating modes if:

- fixturing can be designed that keeps local deformations from causing failure.
- great care is taken in the processing of the force signal so as to obtain valid, calibrated FRF's; not just responses (SDRC has done some development work in this area; beware, it is not sufficient to simply do an FFT on the force signal).
- the response transducers are sensitive enough to pick up extremely low amplitude, low frequency vibration.
- if enough ensembles are collected to allow significant averaging so as to reduce the effects of noisy signals.

3. Since it is obvious that tests to obtain a complete and valid modal model of a containment building will be much more involved than tests to obtain only natural frequencies, mode shapes, and damping, it is probably instructive to document when it may be advantageous to expend the extra effort of getting a modal model from tests.

   When it is desired to obtain a model for evaluating (only) the effects of:

   a) a different soil stiffness
   b) changes in damping
   c) different earthquakes

   then it is not necessary to spend the time and money to develop finite element models. These types of changes can be done just as reliably from a test model as from a finite element model. It is often cheaper and quicker to obtain the test model.

   For extremely difficult-to-test structures (like the HDR containment building) the cost tradeoffs have to be very carefully evaluated. It <u>may</u> be that a finite element model (correlated by a relatively simple modal test to get only natural frequencies, mode shapes, and modal damping) is the cheapest way to go. It should be pointed out, however, that the modal tests performed in 1979 are not, in SDRC's opinion, comprehensive enough to validate a finite element, despite developing a modal model from test.

4. If SDRC can be of any further assistance in this activity, the next test program, how to analytically model the soil/structure interface, how to use finite element techniques in these types of structures, etc. feel free to call Ed Peterson, Dr. Gareth Thomas, or Dr. Jesús Suárez.

II. DATA PRESENTATION

II.1 DUAL ROTATING MASS

Figure 4 is a typical FRF that has been included to document the type and location of relavent data on a bode plot as produced by MODAL-PLUS.

Figure 5 is a sketch of the locations of the response measurements.

The location that was used for the dual rotating mass exciters was ideal for the first four modes of the system. Figures 6 and 7 show the well defined peaks in the Bode plots that occur in the 1.4 - 1.5 Hz and the 2.5 - 2.7 Hz regions. Due to the (near) symmetry of the containment building, it is not at all surprising to find (nearly) repeated modes. The 1.4 Hz X-direction mode and the 1.5 Hz Z-direction mode are one such pair and the 2.5 Hz X-direction mode and 2.7 Hz Z-direction mode are another pair of modes.

It was a relatively easy task to get good reliable modal model information on these four modes by using the Multi-Function MDOF capability in MODAL-PLUS V6 (See appendix D). Figures 8-15 document (graphically and by listings) the mode shapes of these first four modes. Many geometry points had only one direction measured and some points were not measured at all for this frequency range; therefore, there are many zeros in the mode shape listings. This mearly represents missing data and is not basically harmful to the model. For purposes of the shape listing (only) a normalization routine was used that set the largest eigenvector to unity. This was, unfortunately, a very simple routine that resulted in the largest amplitude being close to, but not exactly, unity and resulted in an extreme round off error that dropped anything smaller than 0.010. This round off error is only in the listing routine, so the model itself retains much larger dynamic range. Figure 16 shows the modal mass and modal stiffness results for these first 4 modes. The units for all of the analysis are Meters - Kilograms - Seconds so mass, stiffness, and damping numbers are all consistant. Although the algorithms print out frequency and damping values to several decimal places, the reader is advised to round off all frequencies to 1 decimal place and all viscous damping ratios to the nearest percent.

Once the very low frequency band is left (i.e., below 5 Hz) the picture becomes very cloudy. This is a big problem from a modal modeling viewpoint since it is extremely poor practice to "skip" modes. Therefore as we go higher in frequency, as soon as we cannot adequately define a mode, we must stop and only use that modal model below the frequency where we stopped.

Based on our judgement it appears that there are several (6 or 7) modes in the 5-8 Hz region that are poorly excited by the 533X, 533Z and 534 exciter locations*. These modes do not stand out very well at all at the various driving point exciter locations but there is clearly resonant response at other response locations (see Figures 17 and 18).

Often it is desired to see what natural frequencies stand out on various subsystems. One way to find out is to sum together the FRF's from various subsystems. In fact, it is often helpful to do this summation by subsystem by direction. This yields valuable information and is a mode shape of sorts. That is for one particular natural frequency, one can tell which part of the structure is active and which direction is most active in that part of the structure. Since an FRF has phase, it is necessary to multiply each FRF by its complex conjugate before doing the addition. Figures 19 through 26 show the results of this type of summation. Each function is labeled

* See Figure 2

with the exciter location (533X, 533Z or 534) and the set of response points that were used in the summation (these are listed at the top of the page and described verbally in each figure's title---see Figure 5 for the physical locations of the points and the breakdown between so called "inside" points and "outside" points). The conclusion that can be drawn from these summation functions is that there are quite a few modes in the 5-8 Hz range but these modes do not get excited very well by any of the rotating mass exciter locations since these modes do not stand as well as the (pseudo) driving point FRF's. It was impossible, therefore, to get a reliable modal mass for these modes and in fact the confidence level of the mode shapes was so low that they are not included in this report. All we can say is that we have a vague "feeling" that these modes are associated primarily with the truss type structure connected to the containment building (on the right side of Figure 1). The modes in the 7-8 Hz region seem to be excited more by the torsional excitation (534) than by either of the linear locations (53X, 533Z) but again the FRF's on the inside of the containment building on the exciter floor level (e.g. response point 27Z, see Figure 27) does not show the 7-8 Hz modes very well. It is very possible that these may be modes where other parts of the structure are the most active elements but the mode shape has the containment building moving torsionally. Without a better exciter location to look at, it is impossible to define these modes anymore than vague "hunches."

For what it's worth, our "best guess" of the natural frequencies up to 8 Hz of the overall system are: 1.4 Hz, 1.5 Hz, 2.5 Hz, 2.7 Hz, 5.1 Hz, 5.2 Hz, 5.3 Hz, 6.4 Hz, 6.7 Hz, 7.2 Hz, and 7.8 Hz.

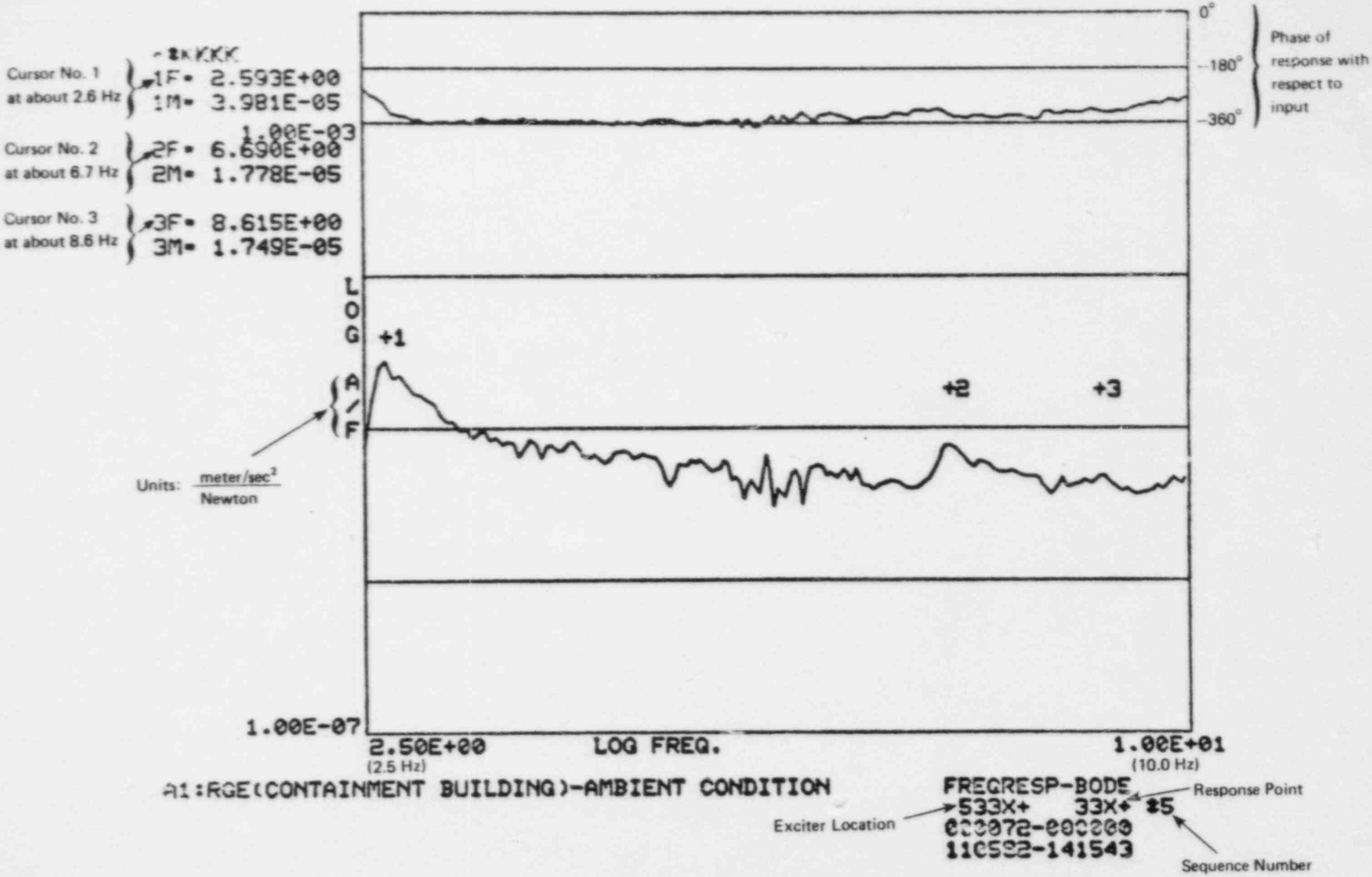
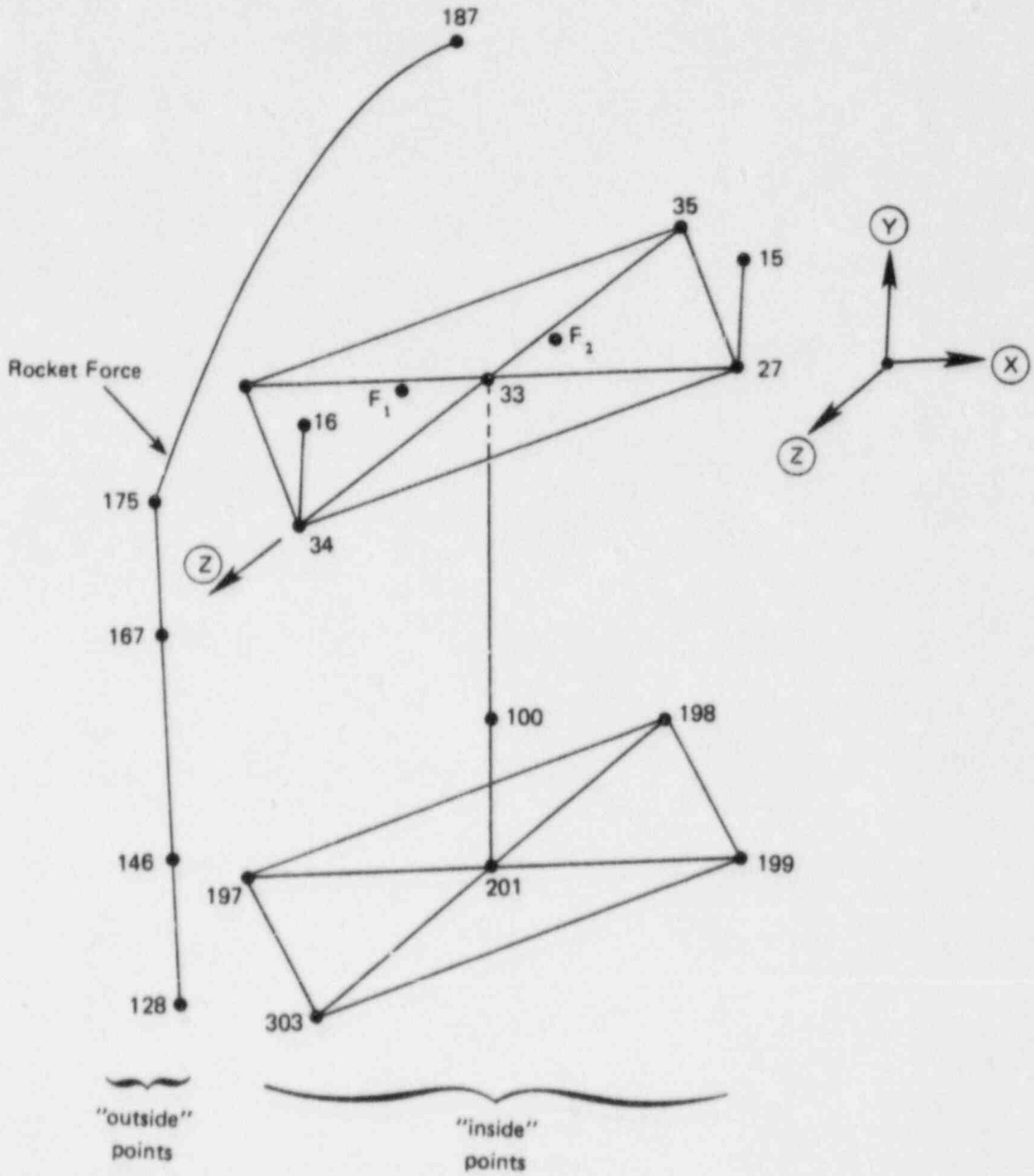


Figure 4
Typical FRF Plot in Bode Format



Note: The point called 203 in original data is labeled 303 in all SDRC data.

Figure 5
Response Locations

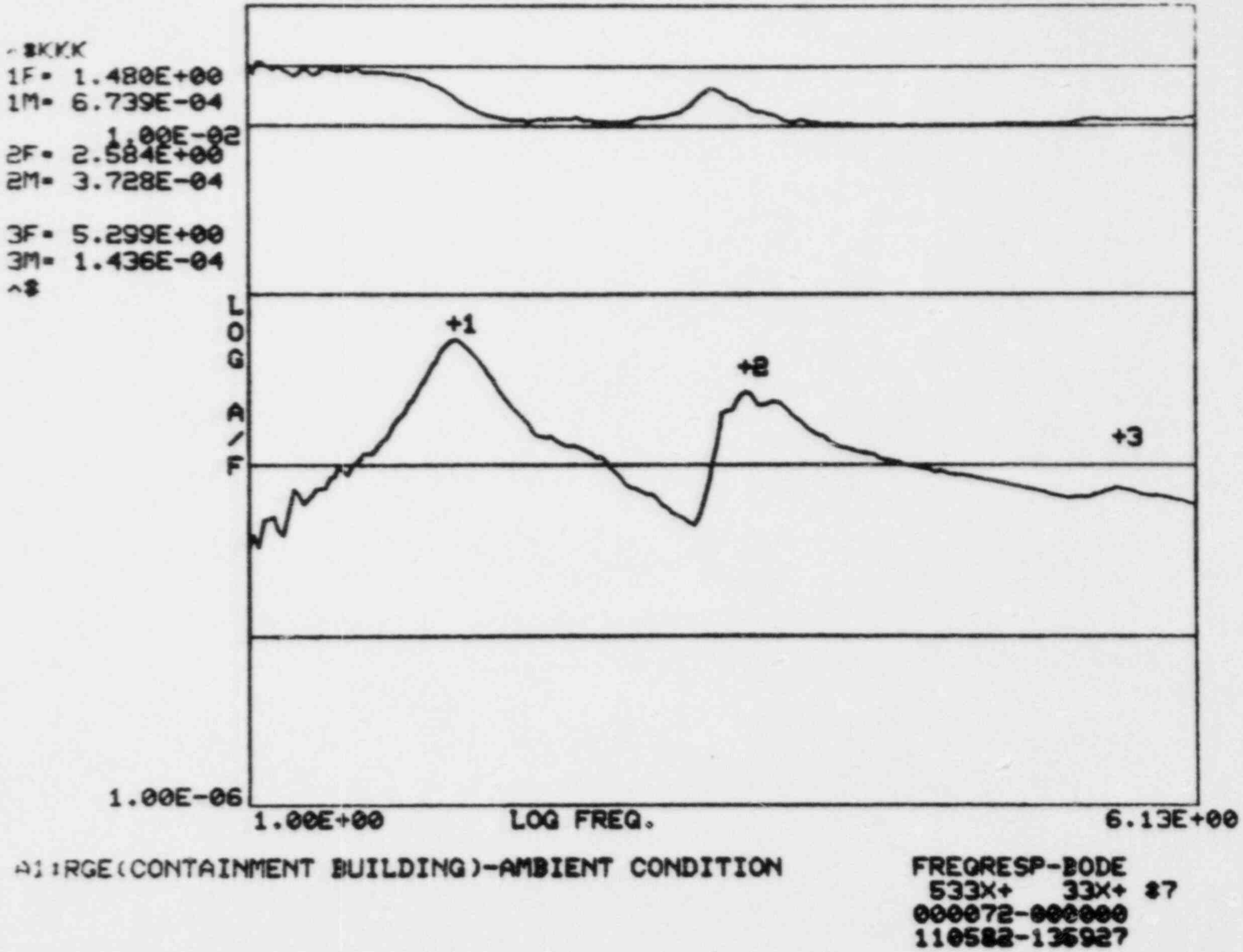

~$KKK
1F= 1.480E+00
1M= 6.739E-04
1.00E-02
2F= 2.584E+00
2M= 3.728E-04
3F= 5.299E+00
3M= 1.436E-04
^$
LOG A/F
+1
+2
+3
1.00E-06
1.00E+00
LOG FREQ.
6.13E+00
A1:RGE(CONTAINMENT BUILDING)-AMBIENT CONDITION
FREQRESP-BODE
533X+ 33X+ $7
000072-000000
110582-136927

Figure 6

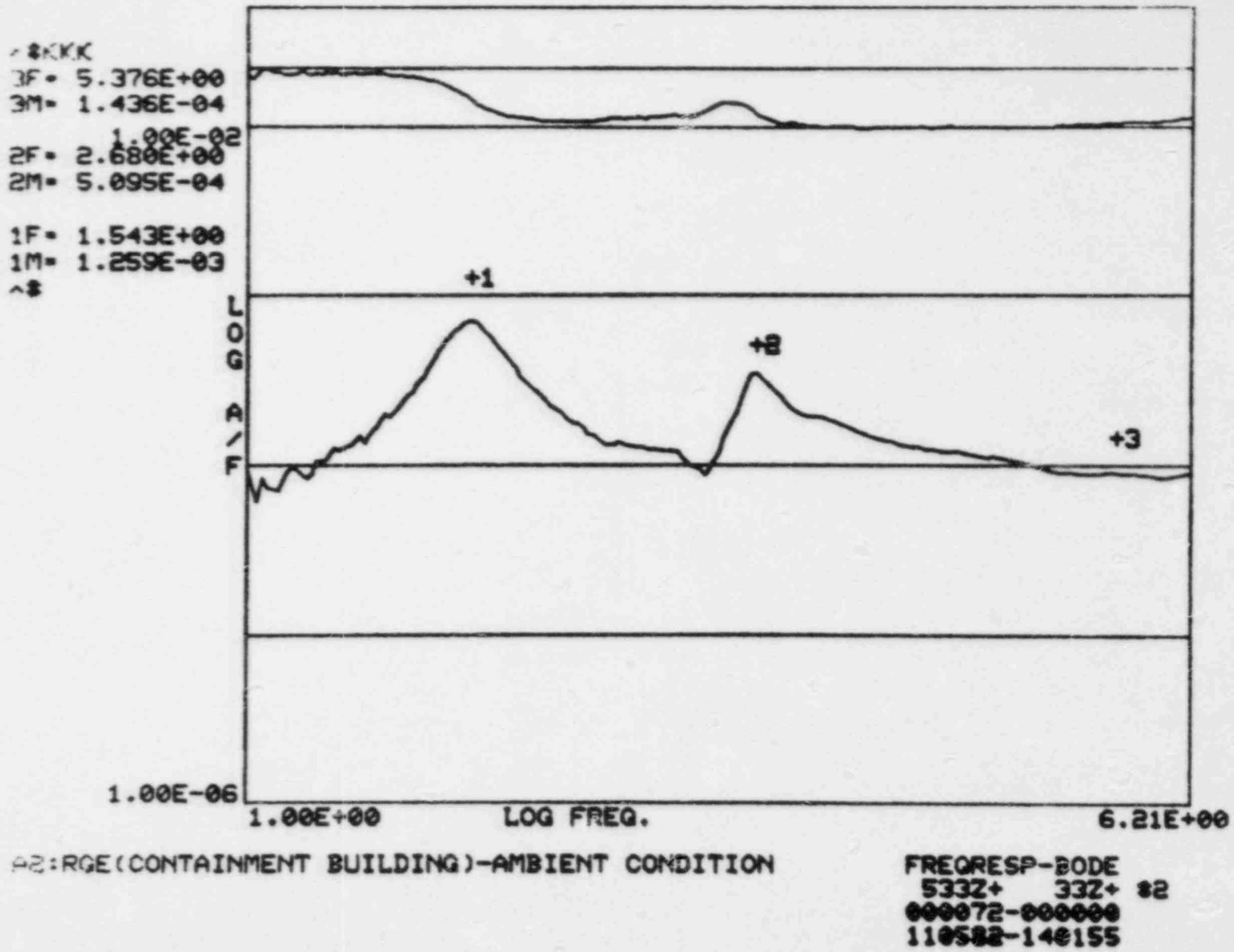

^$KKK
3F= 5.376E+00
3M= 1.436E-04
1.00E-02
2F= 2.680E+00
2M= 5.095E-04
1F= 1.543E+00
1M= 1.259E-03
^$
+1
+2
+3
LOG A/F
1.00E-06
1.00E+00
LOG FREQ.
6.21E+00
A2:RGE(CONTAINMENT BUILDING)-AMBIENT CONDITION
FREQRESP-BODE
533Z+ 33Z+ #2
000072-000000
110582-140155

Figure 7

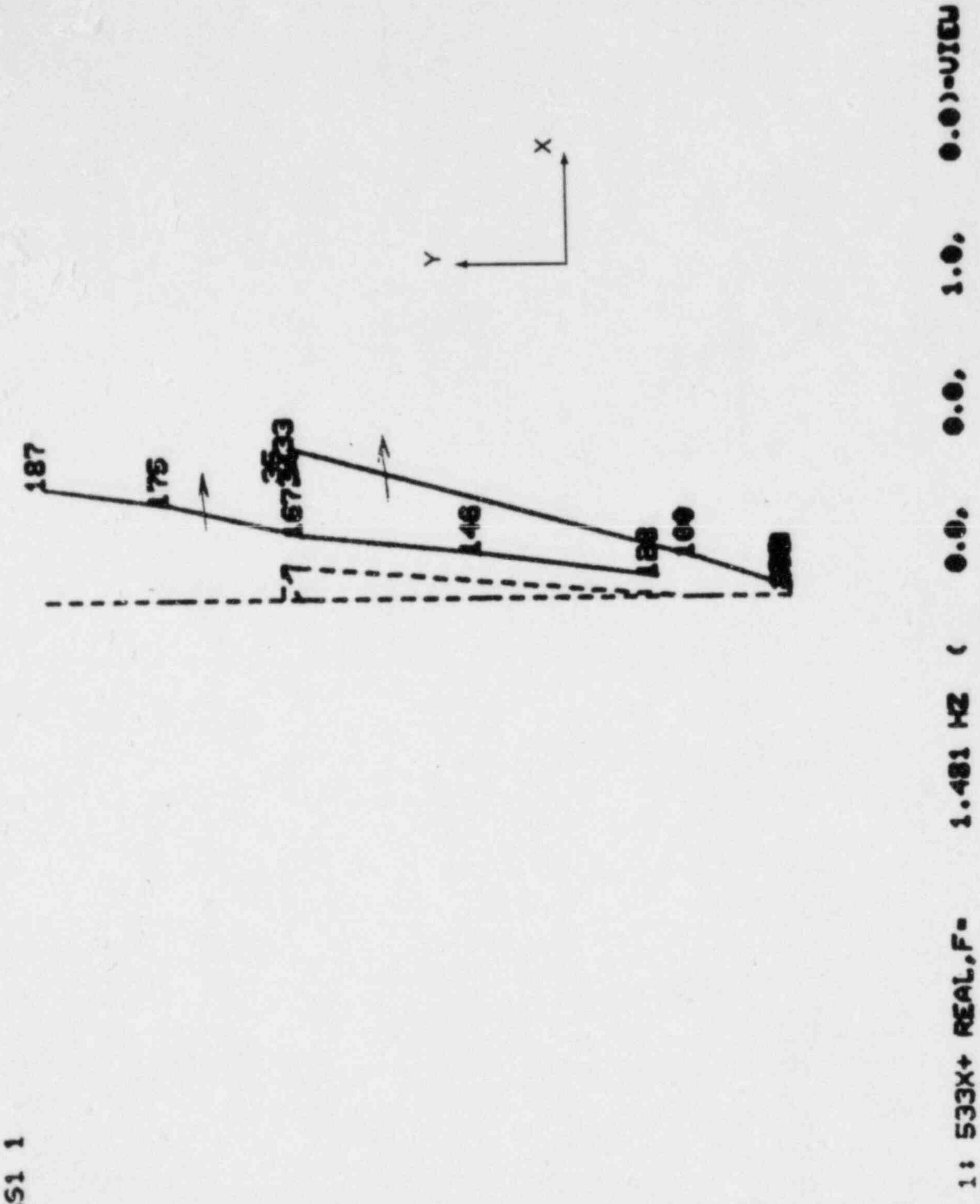

$GS1 1
1: 533X+ REAL,F= 1.481 HZ (0.0, 0.0, 0.0, 1.0, 0.0)-VIEW
187
175
167
148
35
100
X
Y

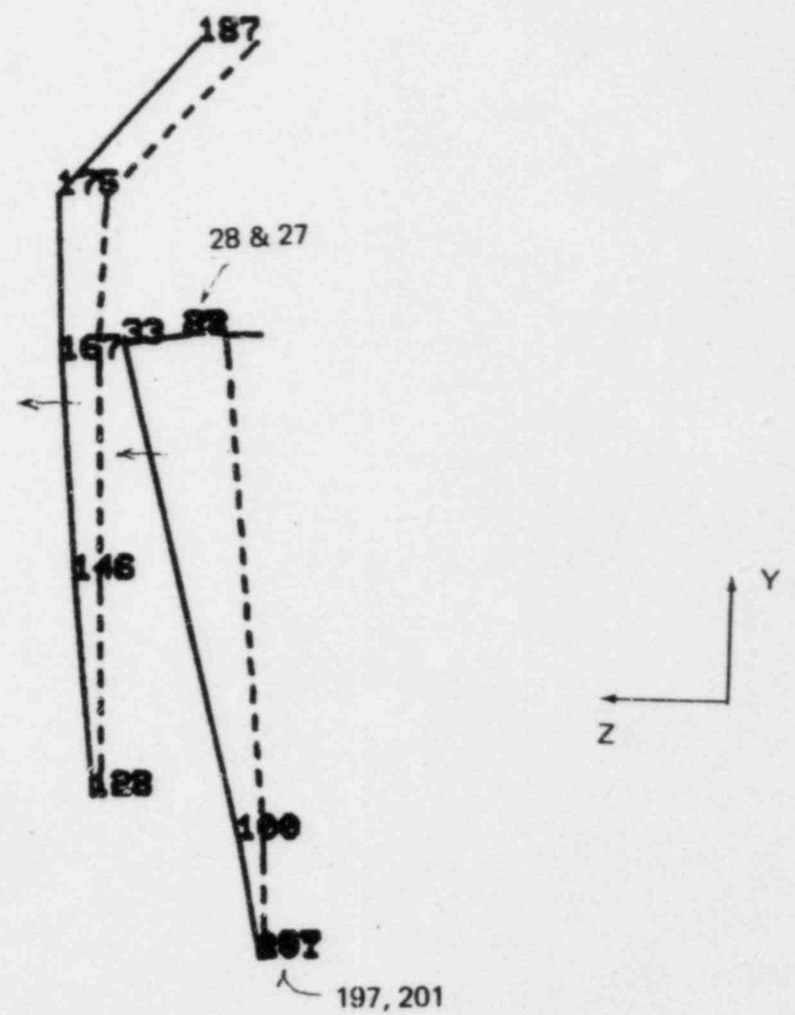
Figure 8

‡
‡
‡
‡?S;LS
MODE SHAPE 1: 533X+ A/F   REAL, FREQ =   1.481 HZ
MODE SHAPE

LOC	X COEFF	Y COEFF	Z COEFF
15	0.0000E+00	0.0000E+00	0.0000E+00
16	0.0000E+00	0.0000E+00	0.0000E+00
17	0.0000E+00	0.0000E+00	0.0000E+00
27	0.0000E+00	0.0000E+00	0.0000E+00
28	0.0000E+00	0.0000E+00	0.0000E+00
33	9.0525E-01	0.0000E+00	0.0000E+00
34	9.0525E-01	0.0000E+00	0.0000E+00
35	9.9285E-01	0.0000E+00	0.0000E+00
100	3.1349E-01	0.0000E+00	0.0000E+00
128	1.5674E-01	0.0000E+00	0.0000E+00
146	3.6575E-01	0.0000E+00	-5.2238E-02
167	5.2253E-01	0.0000E+00	-1.5674E-01
175	7.8378E-01	0.0000E+00	5.2238E-02
187	9.4058E-01	0.0000E+00	0.0000E+00
197	0.0000E+00	1.0448E-01	0.0000E+00
198	0.0000E+00	0.0000E+00	0.0000E+00
199	0.0000E+00	-1.0448E-01	0.0000E+00
201	5.2238E-02	0.0000E+00	0.0000E+00
303	5.2238E-02	0.0000E+00	0.0000E+00
533	9.7424E-01	-5.2238E-02	0.0000E+00

‡

Figure 9



1: 533Z+ REAL,F= 1.534 HZ (1.0, 0.0, 0.0, 0.0)=VIEW

Figure 10

```
*
*
*
*?S;LS
MODE SHAPE 2: 533Z+ A/F    REAL, FREQ =       1.534 HZ
MODE SHAPE
```

LOC	X COEFF	Y COEFF	Z COEFF
15	-1.2450E-01	0.0000E+00	0.0000E+00
16	0.0000E+00	0.0000E+00	0.0000E+00
17	0.0000E+00	0.0000E+00	8.3006E-01
27	0.0000E+00	0.0000E+00	7.0557E-01
28	0.0000E+00	0.0000E+00	6.6406E-01
33	-4.1479E-02	-4.1479E-02	9.9610E-01
34	0.0000E+00	0.0000E+00	0.0000E+00
35	0.0000E+00	0.0000E+00	0.0000E+00
100	0.0000E+00	0.0000E+00	2.0752E-01
128	0.0000E+00	0.0000E+00	4.1479E-02
146	0.0000E+00	0.0000E+00	2.0752E-01
167	8.2988E-02	0.0000E+00	3.3201E-01
175	-4.1479E-02	0.0000E+00	4.5654E-01
187	0.0000E+00	0.0000E+00	5.3953E-01
197	0.0000E+00	0.0000E+00	0.0000E+00
198	0.0000E+00	4.1479E-02	0.0000E+00
199	0.0000E+00	0.0000E+00	0.0000E+00
201	0.0000E+00	0.0000E+00	0.0000E+00
303	0.0000E+00	0.0000E+00	0.0000E+00
533	-7.4150E-02	-6.4702E-02	9.9863E-01

```
*
```

Figure 11

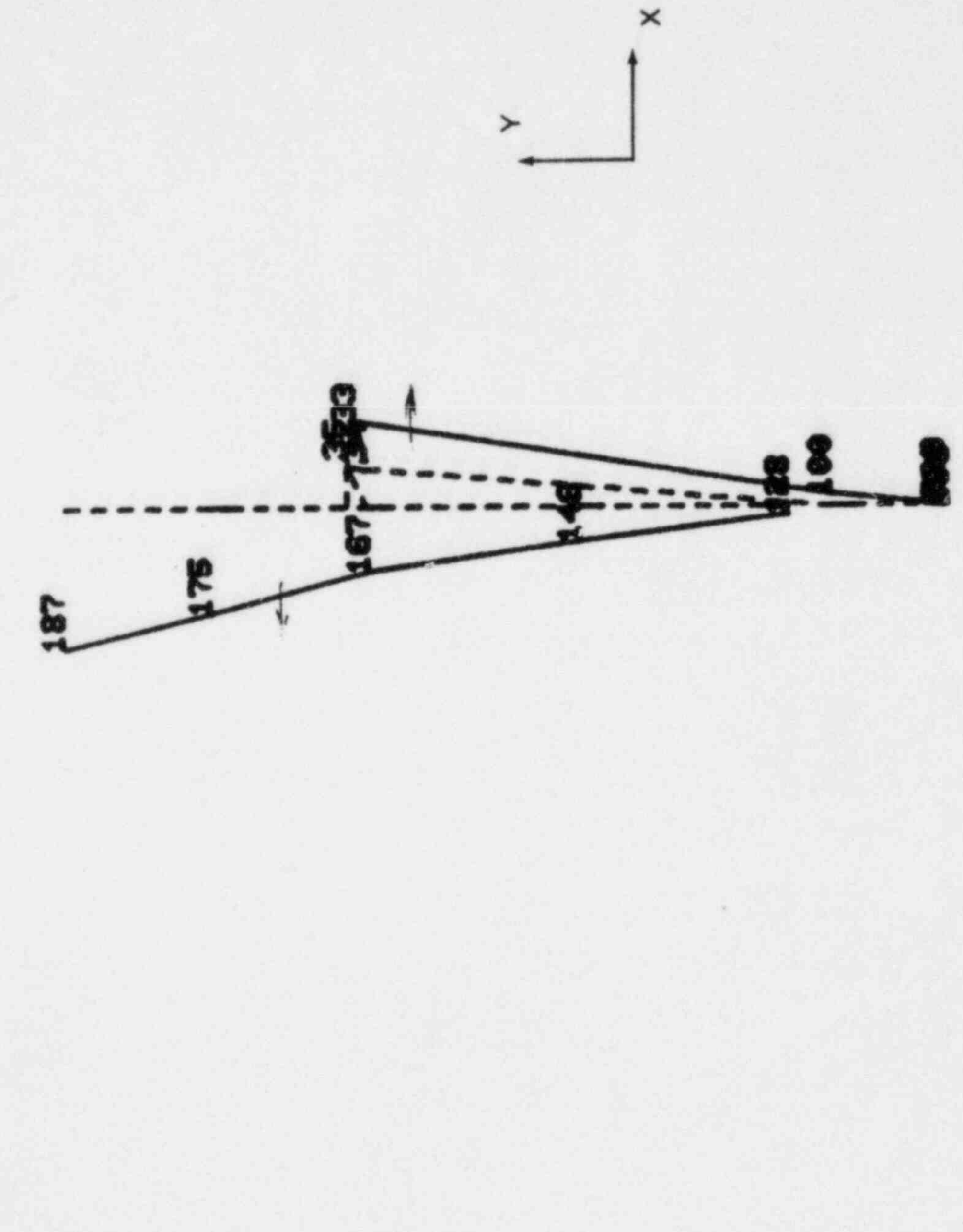


Figure 12

```
*
*
*
*?S;LS
MODE SHAPE 3: 533X+ A/F    REAL, FREQ =        2.538 HZ
MODE SHAPE
  LOC    X COEFF       Y COEFF       Z COEFF
   15  0.0000E+00  0.0000E+00  0.0000E+00
   16  0.0000E+00  0.0000E+00  0.0000E+00
   17  0.0000E+00  0.0000E+00 -1.8827E-01
   27  0.0000E+00  0.0000E+00 -1.8827E-01
   28  0.0000E+00  0.0000E+00 -1.4120E-01
   33 -2.8243E-01  0.0000E+00 -1.8827E-01
   34 -2.8243E-01  0.0000E+00  0.0000E+00
   35 -3.2950E-01  0.0000E+00  0.0000E+00
  100 -4.7046E-02  0.0000E+00  0.0000E+00
  128  4.7046E-02  0.0000E+00  0.0000E+00
  146  2.3535E-01  0.0000E+00  4.7046E-02
  167  4.2365E-01  0.0000E+00  9.4122E-02
  175  7.0611E-01  0.0000E+00  4.2365E-01
  187  9.9970E-01  0.0000E+00  3.7658E-01
  197  0.0000E+00  5.8792E-02  0.0000E+00
  198  0.0000E+00  1.4675E-02  0.0000E+00
  199  0.0000E+00 -4.4086E-02  0.0000E+00
  201  0.0000E+00  0.0000E+00  0.0000E+00
  303  0.0000E+00  0.0000E+00  0.0000E+00
  533 -3.1220E-01  4.4086E-02 -2.3520E-01
*
```

Figure 13

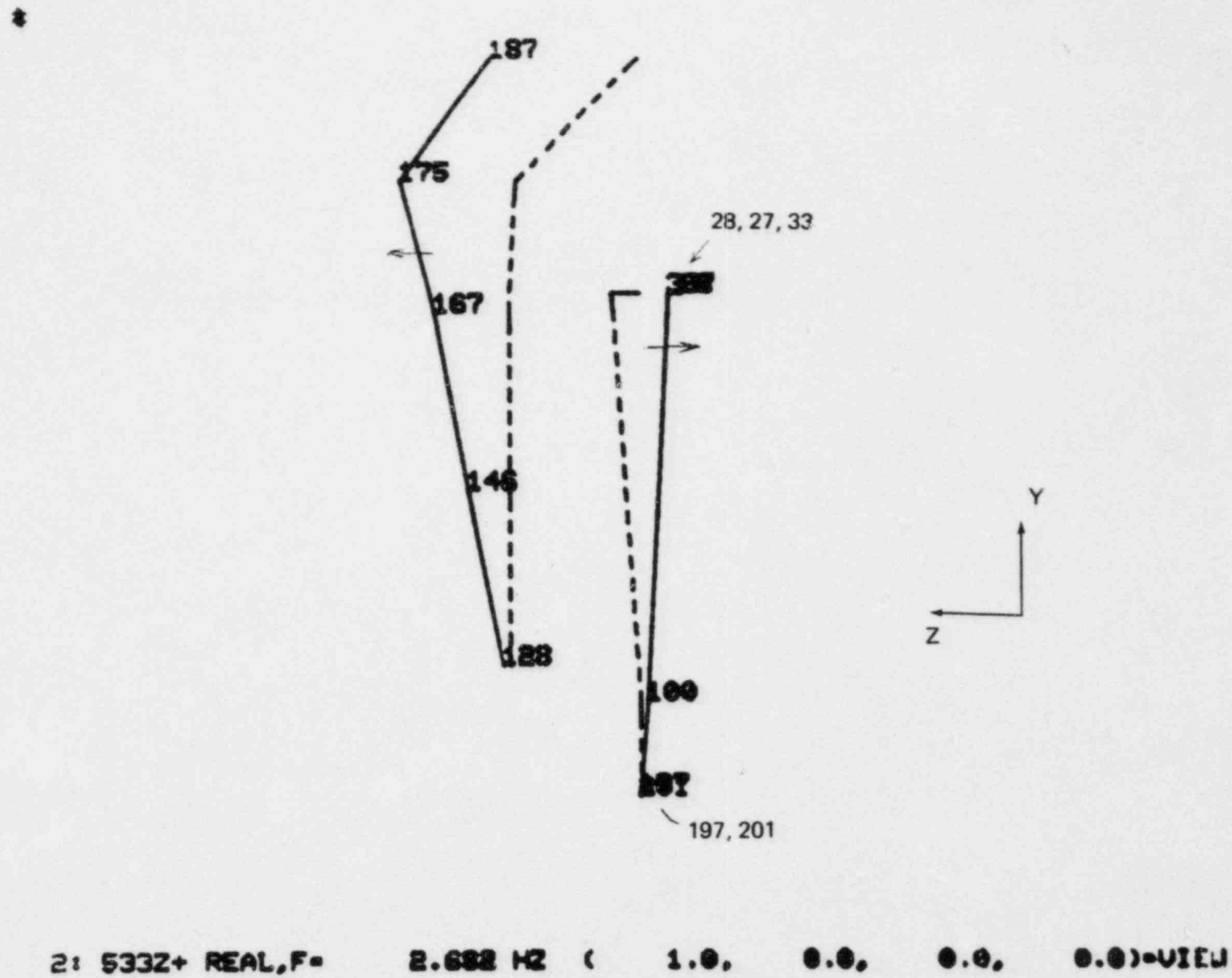

187
175
167
146
128
28, 27, 33
100
197, 201
Y
Z
2: 5332+ REAL,F= 2.682 HZ (1.0, 0.0, 0.0, 0.0)=VIEW

Figure 14

$
$
$
$
$?S;LS

MODE SHAPE 4: 533Z+ A/F   REAL, FREQ =   2.682 HZ

MODE SHAPE

LOC	X COEFF	Y COEFF	Z COEFF
15	4.9405E-02	0.0000E+00	0.0000E+00
16	0.0000E+00	0.0000E+00	0.0000E+00
17	0.0000E+00	0.0000E+00	-2.9646E-01
27	0.0000E+00	0.0000E+00	-2.4705E-01
28	0.0000E+00	0.0000E+00	-2.4705E-01
33	0.0000E+00	0.0000E+00	-3.4589E-01
34	0.0000E+00	0.0000E+00	0.0000E+00
35	0.0000E+00	0.0000E+00	0.0000E+00
100	0.0000E+00	0.0000E+00	0.0000E+00
128	0.0000E+00	0.0000E+00	0.0000E+00
146	0.0000E+00	0.0000E+00	2.4705E-01
167	9.8809E-02	0.0000E+00	4.9414E-01
175	-1.4821E-01	0.0000E+00	7.4119E-01
187	-1.9130E-02	0.0000E+00	9.9499E-01
197	0.0000E+00	0.0000E+00	0.0000E+00
198	0.0000E+00	3.8261E-02	0.0000E+00
199	0.0000E+00	0.0000E+00	0.0000E+00
201	0.0000E+00	0.0000E+00	0.0000E+00
303	0.0000E+00	0.0000E+00	0.0000E+00
533	2.8817E-02	5.7087E-03	-3.8525E-01

$

Figure 15

MODE SHAPES NORMALIZED TO LARGEST ABSOLUTE SHAPE VECTOR = 1

FREQUENCY (HERTZ)	MODAL MASS	MODAL STIFFNESS	MODAL DAMPING	NORMAL COEFF	NORMAL VALUE	EQUIVALENT VISCOUS DAMPING RATIO
1.48	20742.	1.79732E+06	15948.	35X+	5.69004E-04	4.1%
1.53	14381.	1.33765E+06	13113.	533Z+	7.34300E-04	4.7%
2.54	6743.5	1.71532E+06	7709.3	187X+	-6.48097E-04	3.6%
2.68	8160.3	2.31840E+06	10586.	187Z+	-6.14512E-04	3.8%

MODAL MASS, STIFFNESS, & DAMPING ARE "REAL" MODE CALCULATIONS

HIT A CARRIAGE RETURN TO CONTINUE JQ2:?*

Figure 16

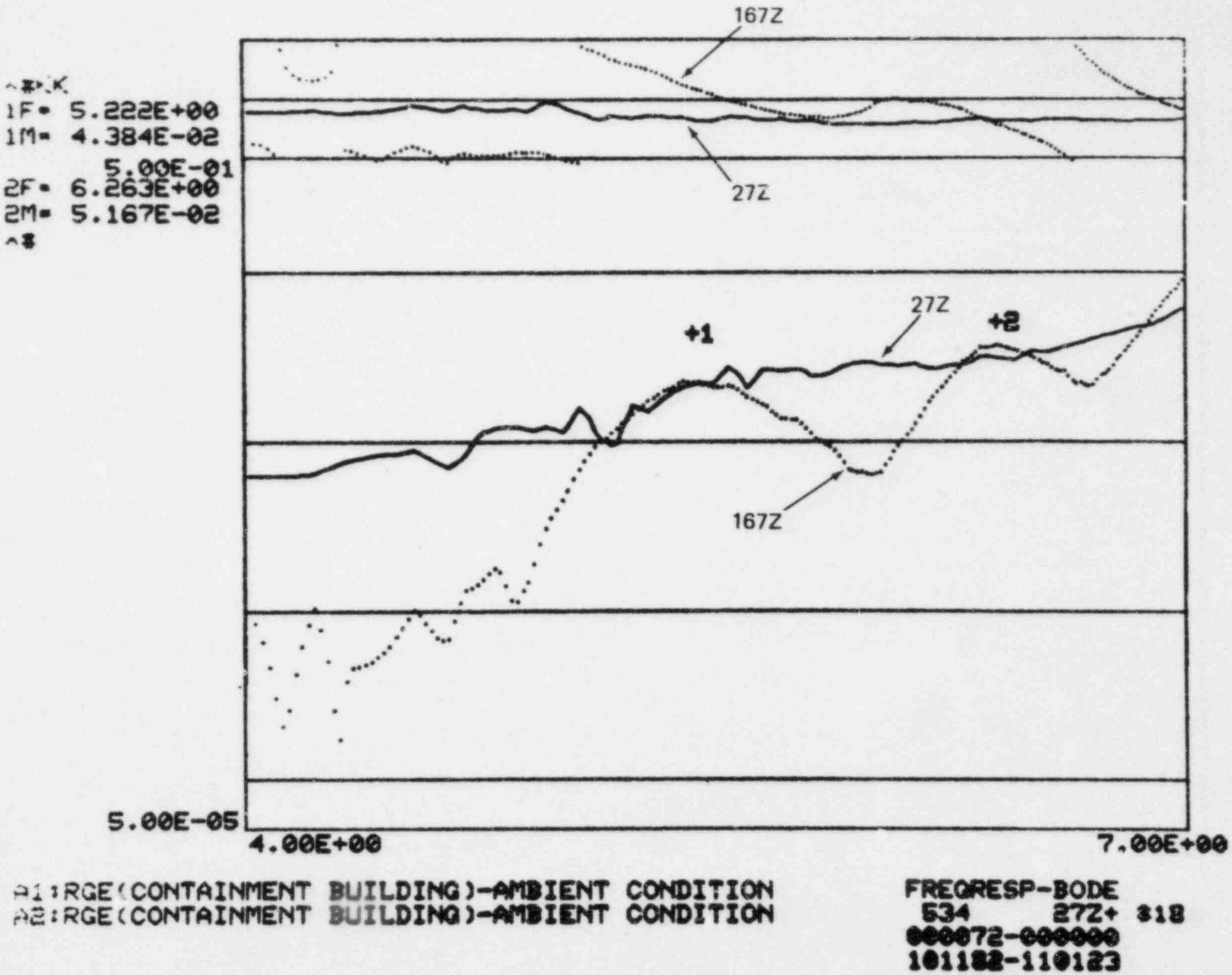
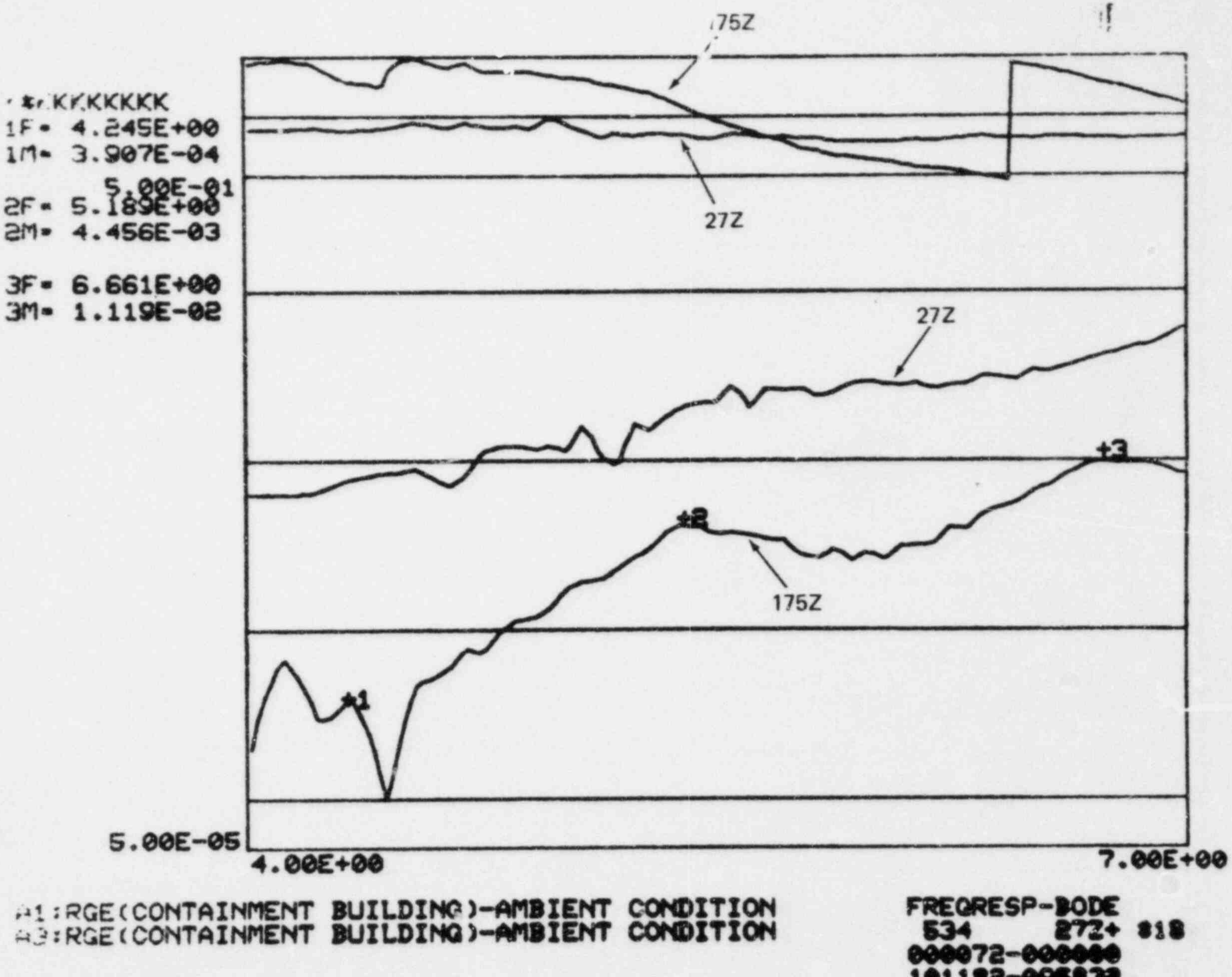

167Z
27Z
1F= 5.222E+00
1M= 4.384E-02
5.00E-01
2F= 6.263E+00
2M= 5.167E-02
27Z
+1
+2
167Z
5.00E-05
4.00E+00
7.00E+00
A1:RGE(CONTAINMENT BUILDING)-AMBIENT CONDITION
A2:RGE(CONTAINMENT BUILDING)-AMBIENT CONDITION
FREQRESP-BODE
534 27Z+ 318
000072-000000
101182-110123

Figure 17



KKKKKKK
1F= 4.245E+00
1M= 3.907E-04
5.00E-01
2F= 5.189E+00
2M= 4.456E-03
3F= 6.661E+00
3M= 1.119E-02
175Z
27Z
27Z
175Z
+1
+2
+3
5.00E-05
4.00E+00
7.00E+00
A1:RGE(CONTAINMENT BUILDING)-AMBIENT CONDITION
A3:RGE(CONTAINMENT BUILDING)-AMBIENT CONDITION
FREQRESP-BODE
534 27Z+ #18
000072-000000
101182-095832

Figure 18

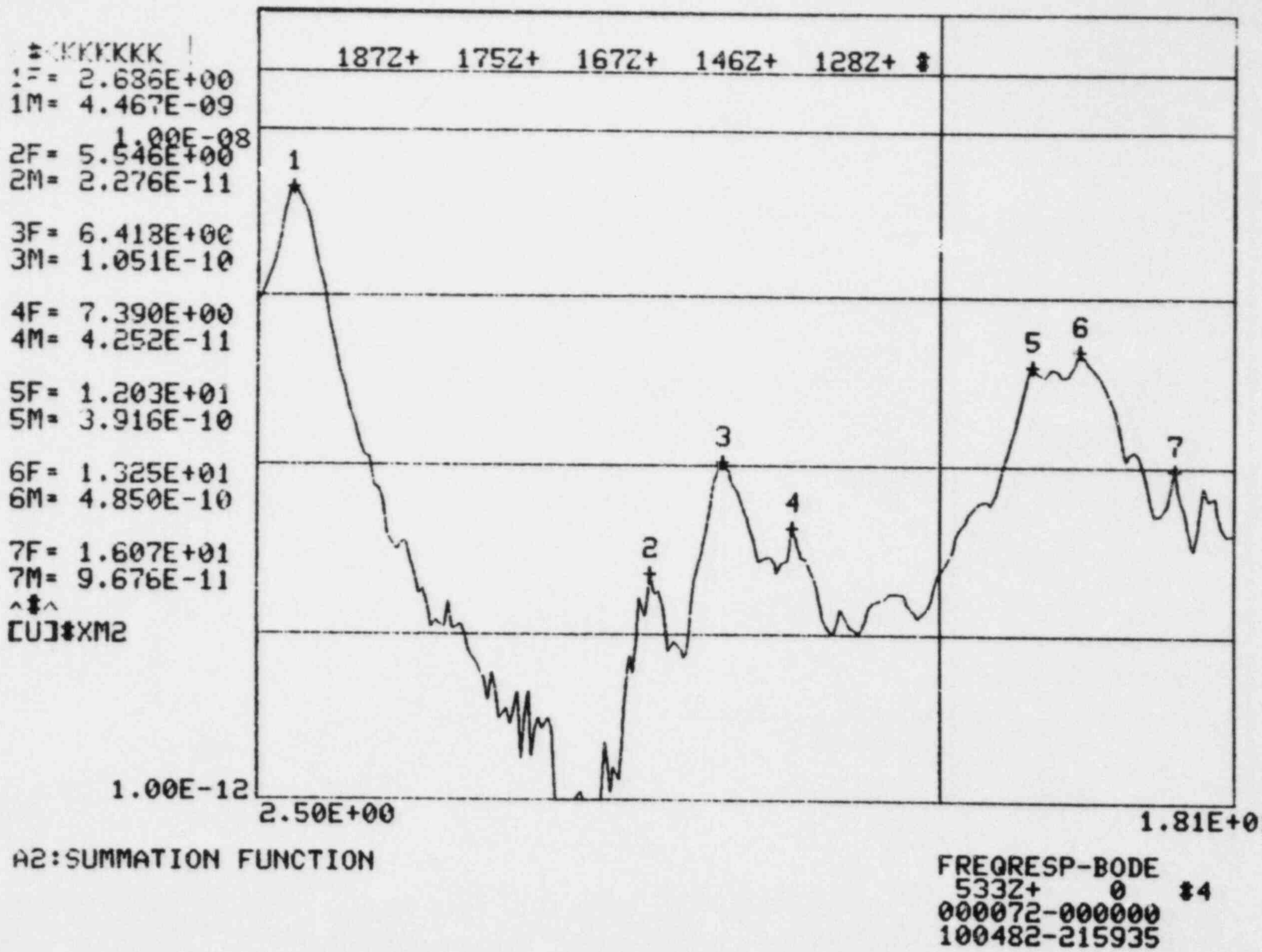


Figure 19
Excite in Z; Sum Z Direction of Outside Points

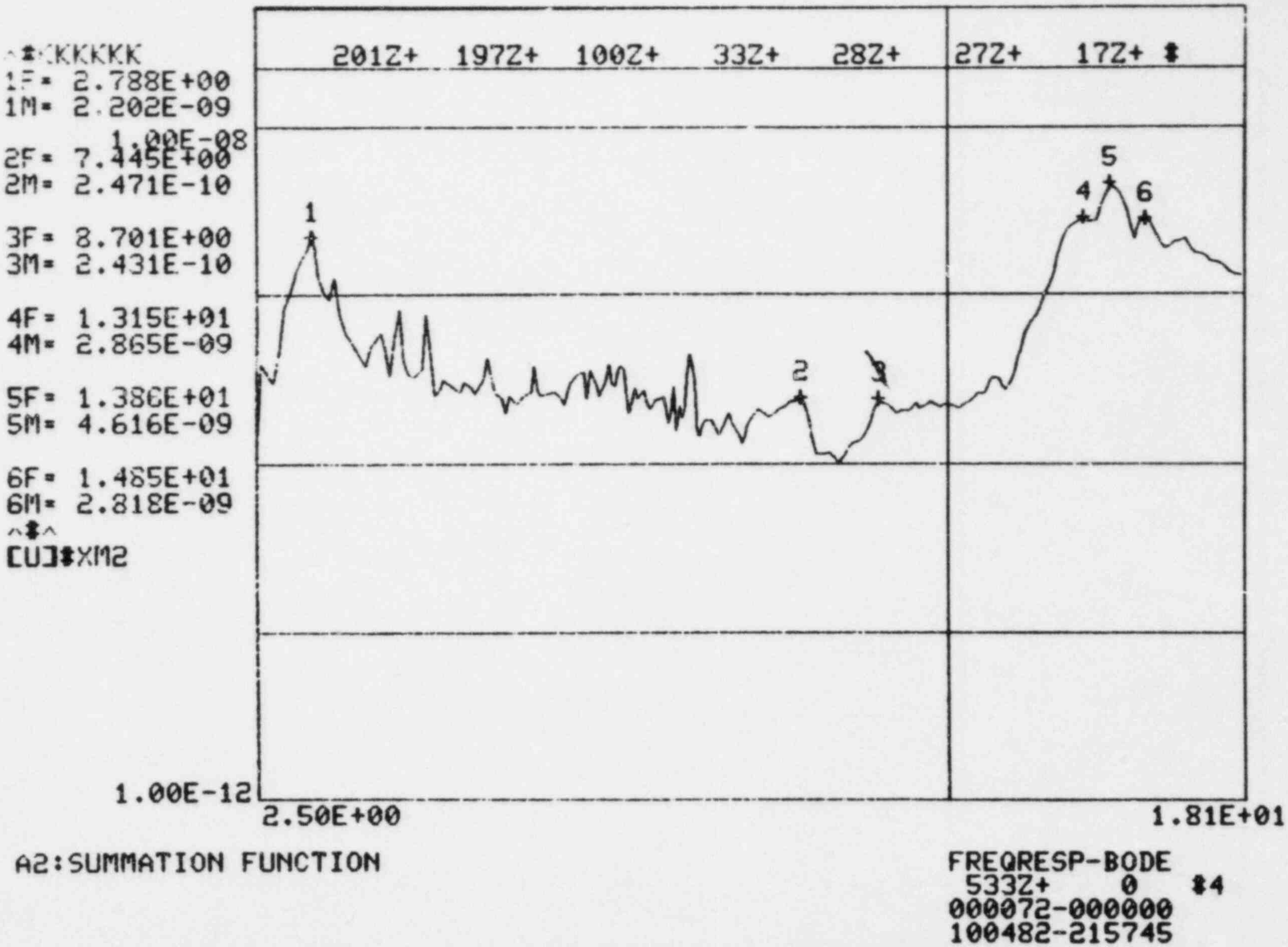


Figure 20
Excite in Z; Sum Z Direction of Inside Points

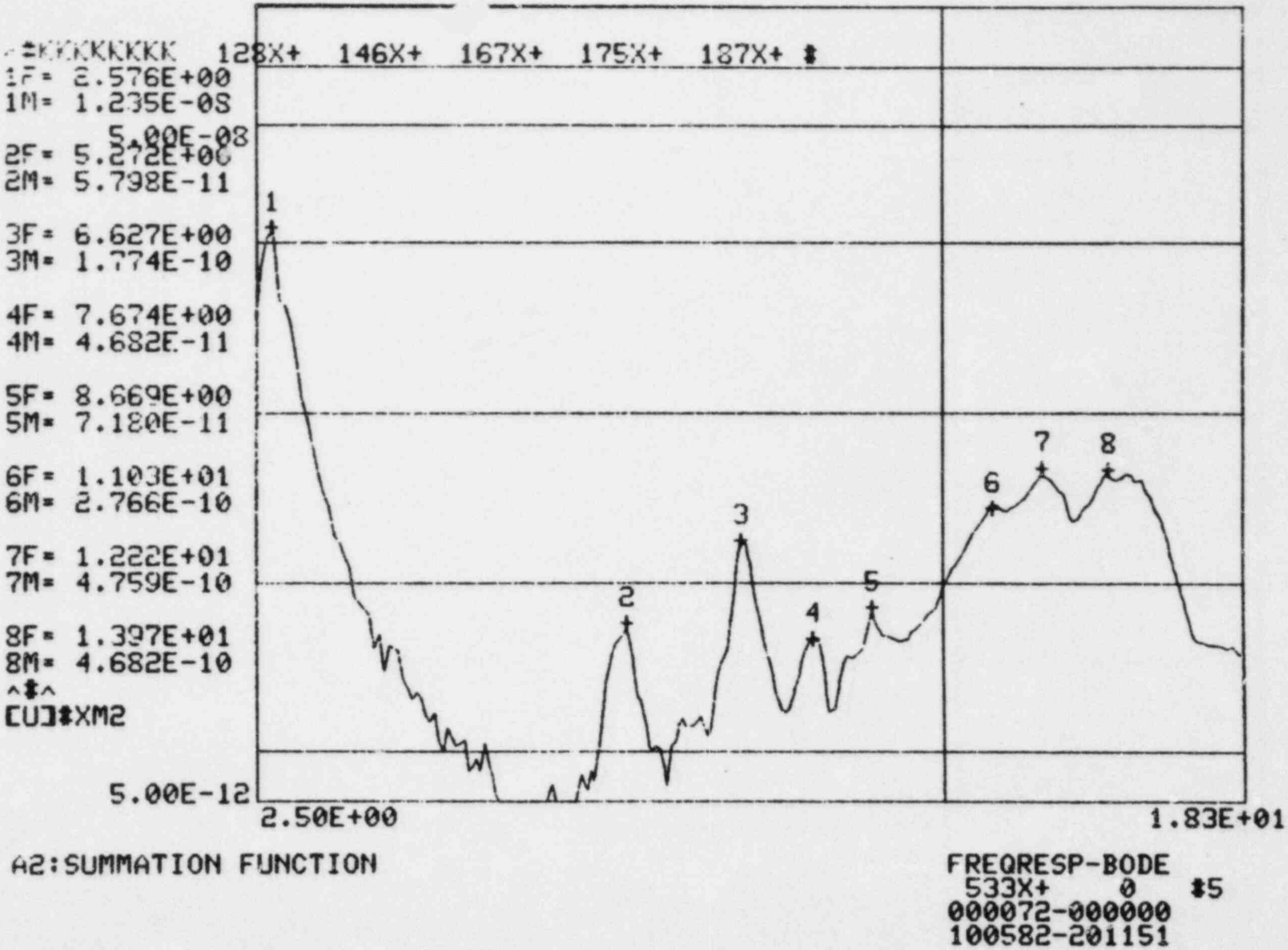


Figure 21
Excite in X; Sum X Direction of Outside Points

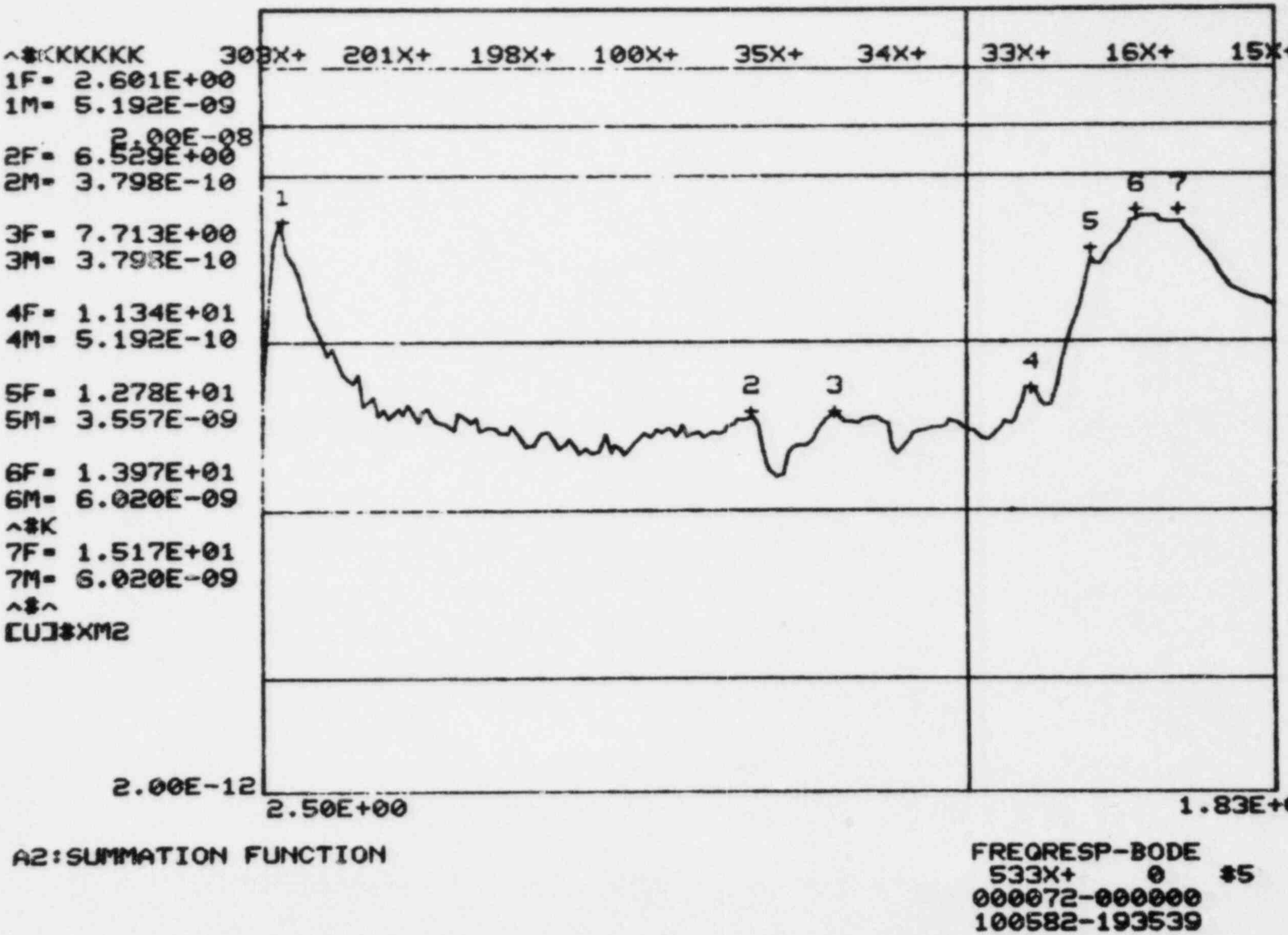


Figure 22
Excite in X; Sum X Direction of Inside Points

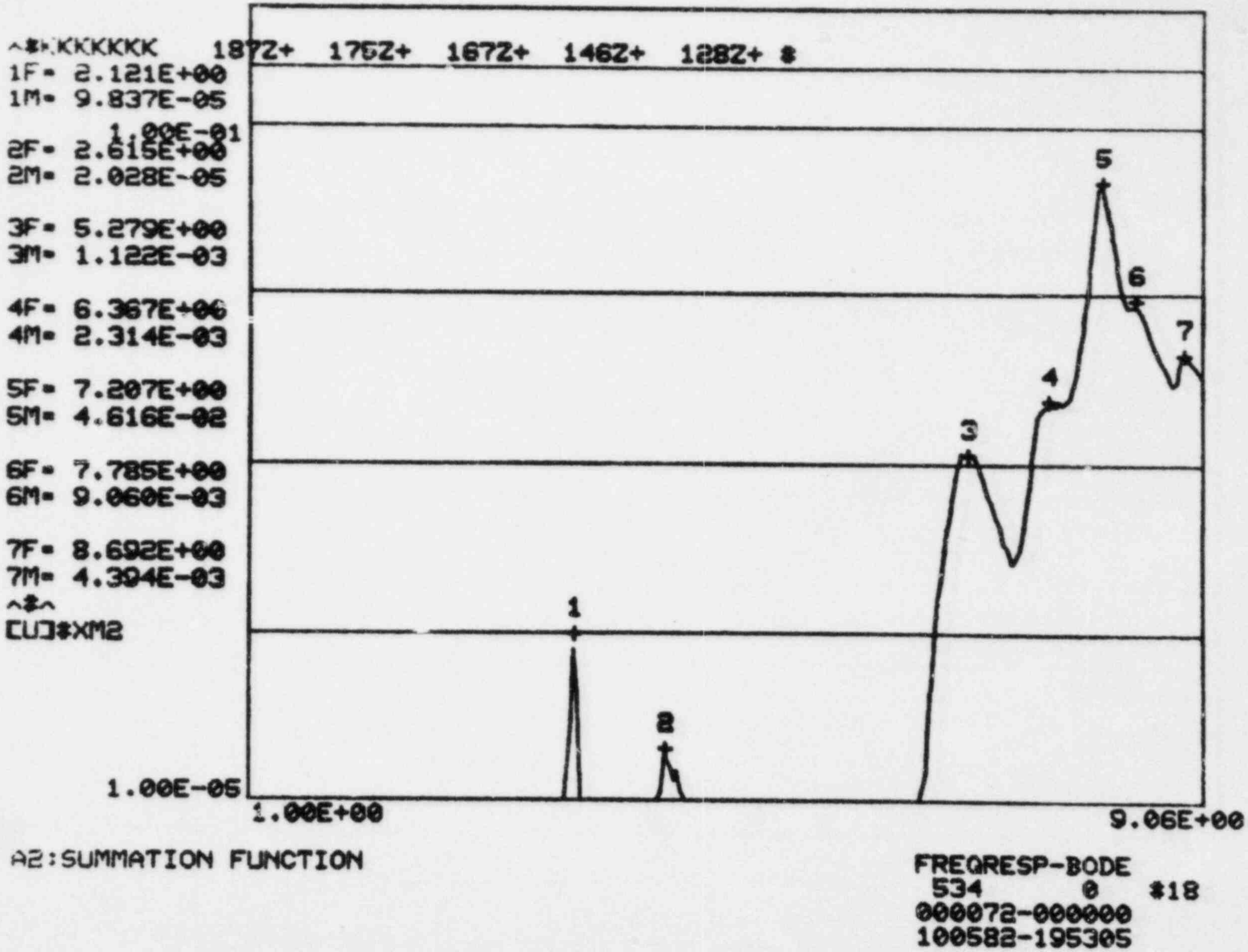


Figure 23
Excite Torsionally; Sum Z Direction Outside Points

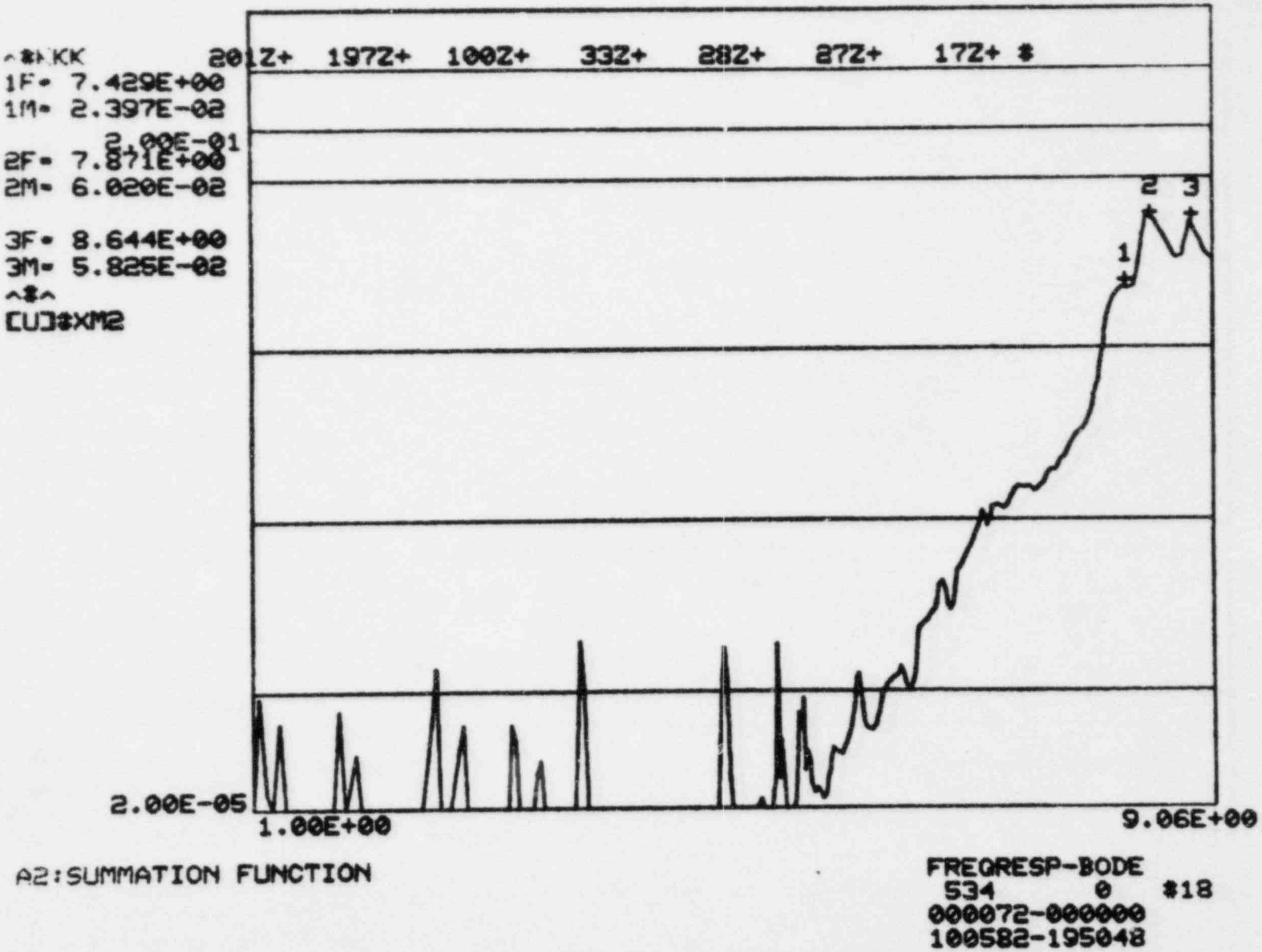


Figure 24
Excite Torsionally; Sum X Directions of Inside Points

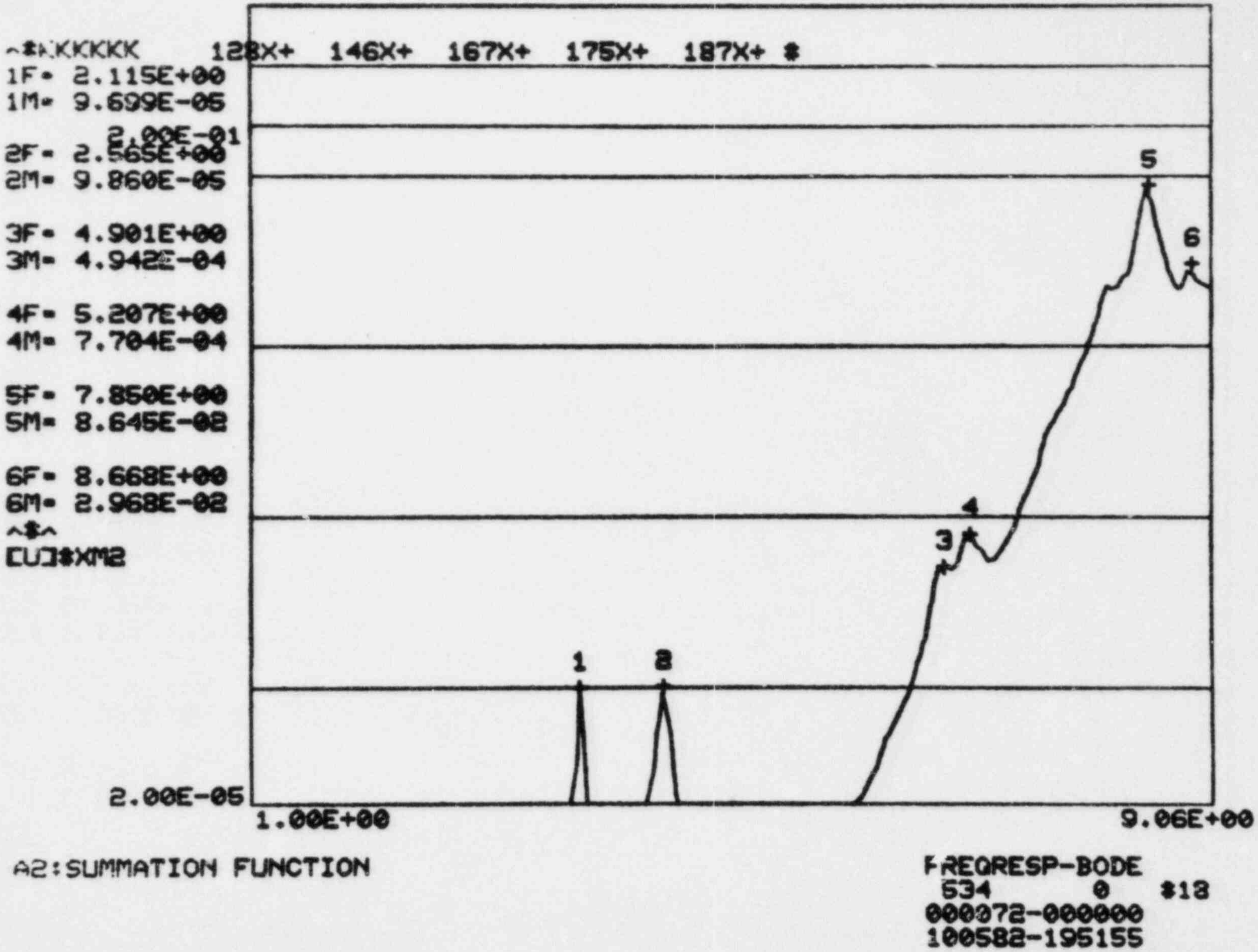


Figure 25
Excite Torsionally; Sum X Direction Outside Points

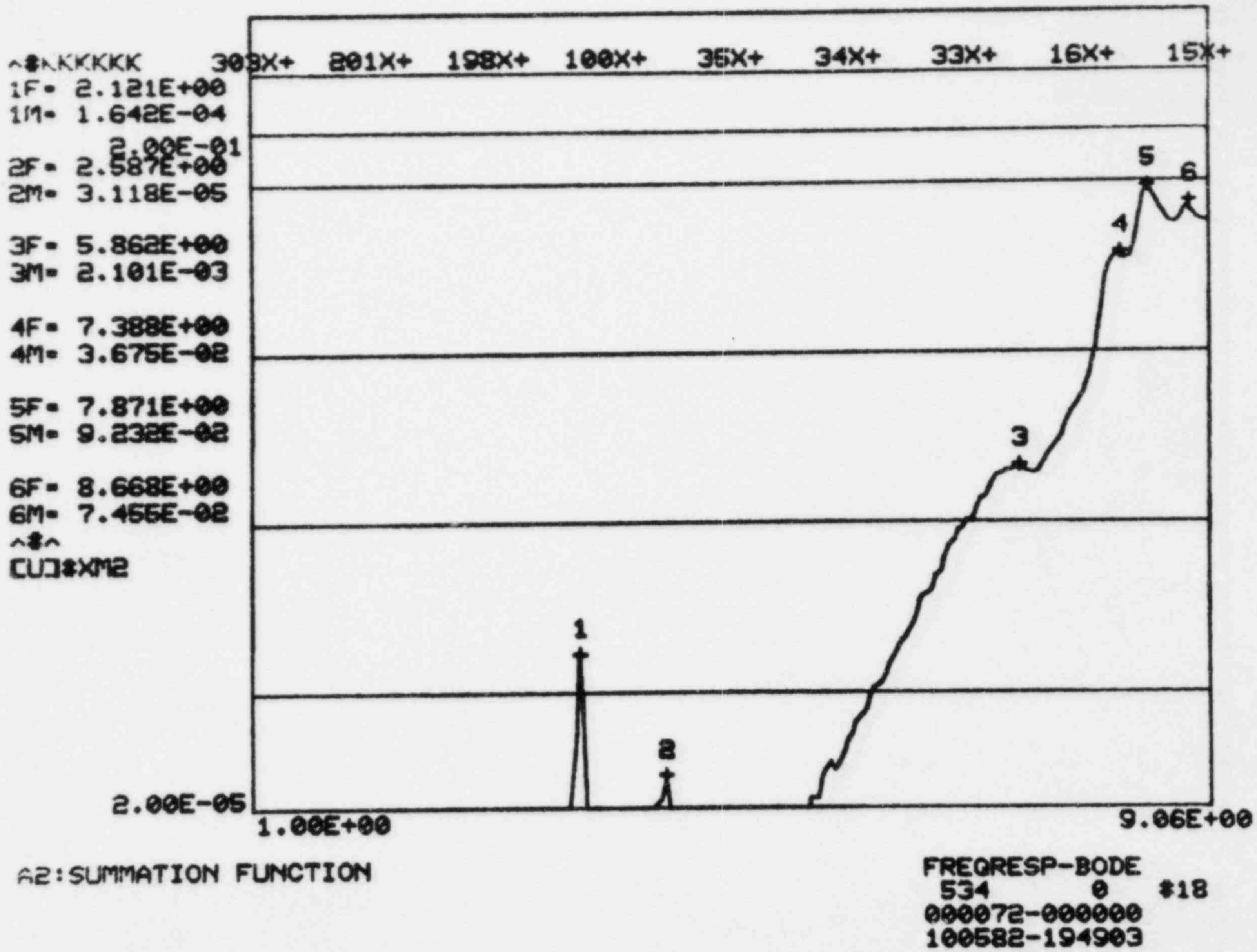
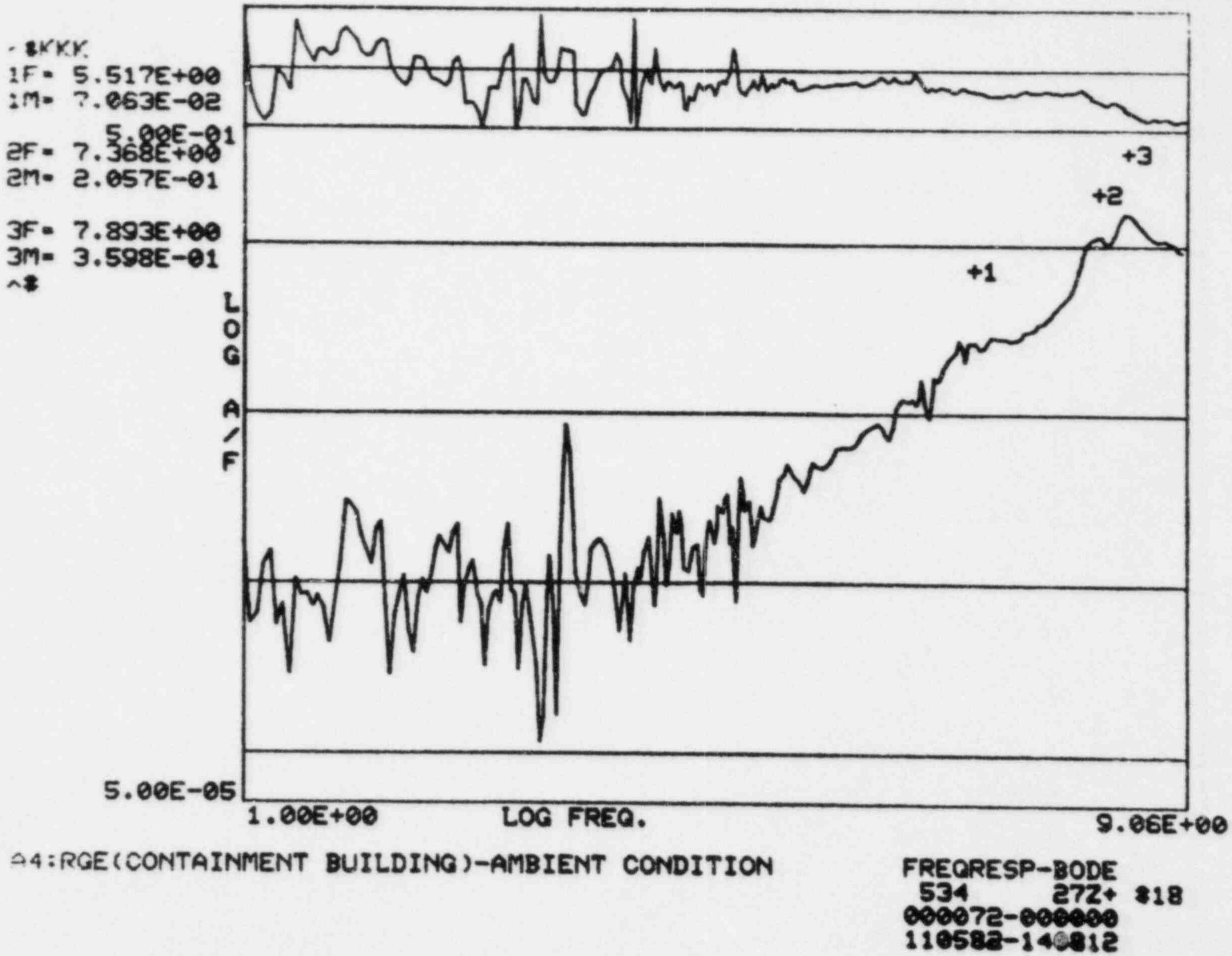


Figure 26
Excite Torsionally; Sum X Directions of Inside Points



1F= 5.517E+00
1M= 7.063E-02
5.00E-01
2F= 7.368E+00
2M= 2.057E-01
3F= 7.893E+00
3M= 3.598E-01
+3
+2
+1
LOG A/F
5.00E-05
1.00E+00
LOG FREQ.
9.06E+00
A4:RGE(CONTAINMENT BUILDING)-AMBIENT CONDITION
FREQRESP-BODE
534 272+ #18
000072-000000

Figure 27

II.2 ROCKET TESTS

Since the rocket tests were the tests that held the most promise (they were single point input, unlike the dual input rotating mass exciter and they had a measured force, unlike the explosion data) this data was felt to have the best chance of yielding a valid modal model.

Unfortunately, this rocket data also had a fatal flaw from a modal modelling viewpoint. The problem this time was a little more subtle that the really fundamental problems that the rotating mass exciter data had but it would have been easy to identify during the test _if_ the test plan would have specified that valid FRF's should be obtained.

The problem is a direct result of the 1/2 second time duration of the rocket force. The frequency content of a mathematically perfect half square wave with a 1/2 second duration (See Figure 28) has minimum energy (nearly zero) in the force spectrum at about 2.0 Hz, 4.0 Hz, ... (see Figure 29). These "zeros" in the force spectra cause erroneous peaks in the FRF since the force is in the denominator.

As can be seen in a sample of the actual data from the rocket test (Figure 30), the response spectrum has "reasonable" looking peaks at about 1.5 Hz, 2.7 Hz, 5.7 Hz, etc. which were already documented as modes of the system. The FRF (Figure 31) for this same response point, however, has a bunch of "mystery modes" at about 2 Hz, 4 Hz, 6 Hz, 8 Hz and 10 Hz. which completely "drown out" the reasonable modes that were seen in the response spectrum. When we look at the frequency content of the rocket input (Figure 32), however, it becomes very apparent that the so called "mystery modes" in the FRF are really caused by minimum values in the force spectrum (the minimum values in Figure 32 have been tagged with the same numbers as the peaks that they caused in Figure 31). This totally botches up the FRF and makes it unusable for the extraction of modal mass.

If rockets are used again, then the duration of the force pulse must be shortened. Figures 33-36 show that pulses with time durations of 0.1 seconds and 0.05 seconds have maximum usable frequencies of about 7 Hz and 15 Hz respectively.

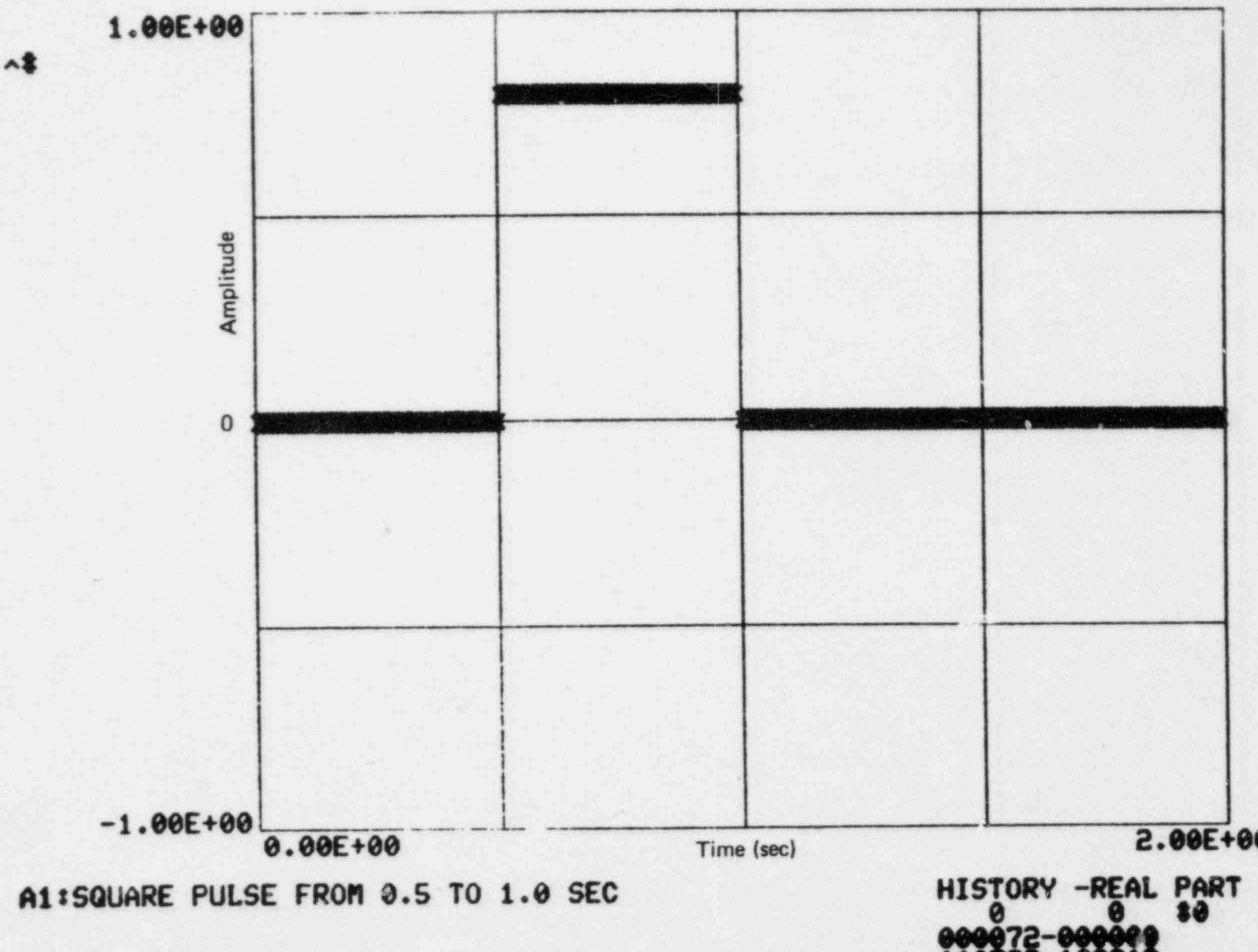
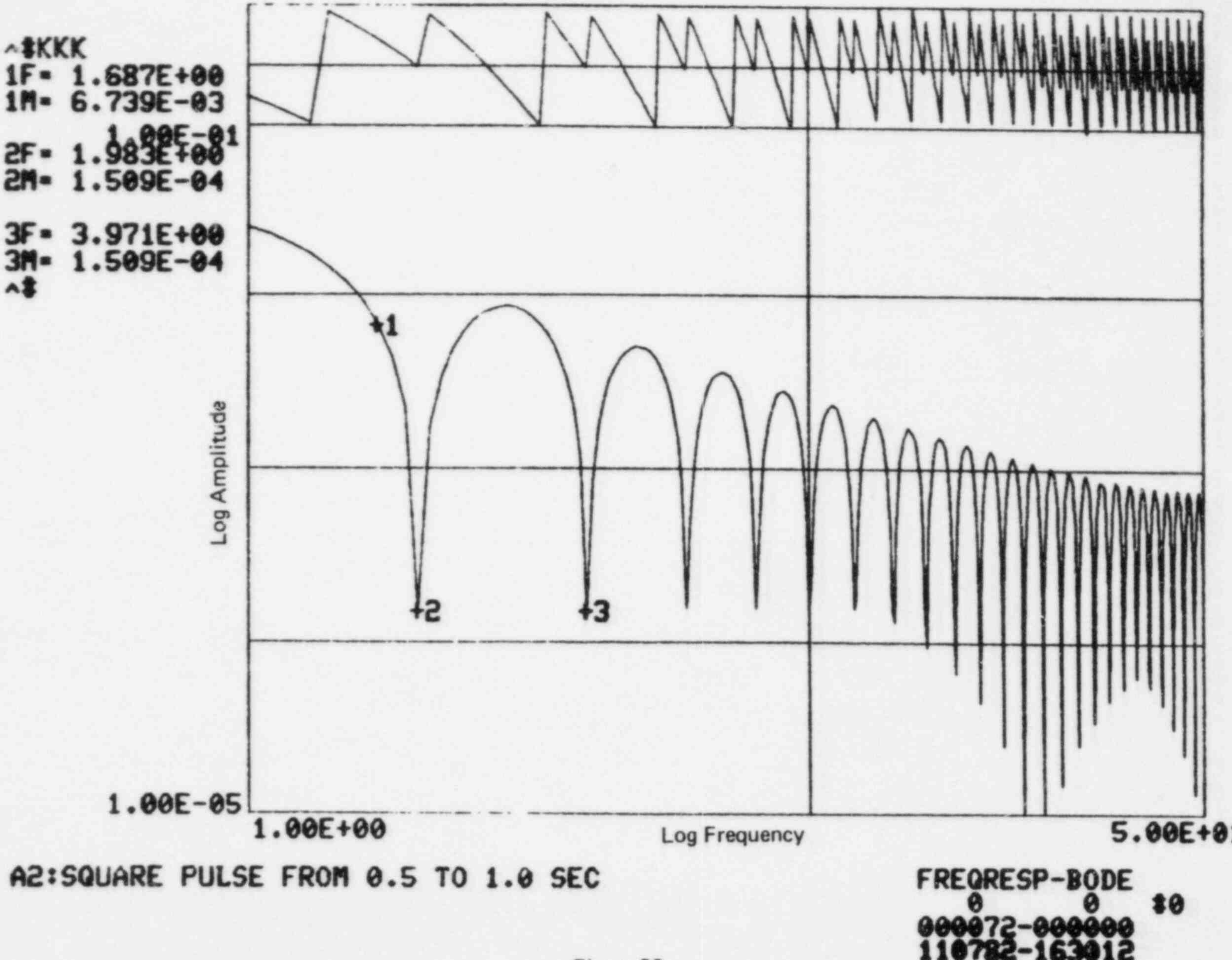


Figure 28
1/2 Second Pulse



^$KKK
1F= 1.687E+00
1M= 6.739E-03
1.00E-01
2F= 1.983E+00
2M= 1.509E-04
3F= 3.971E+00
3M= 1.509E-04
^$
+1
+2
+3
Log Amplitude
1.00E-05
1.00E+00
Log Frequency
5.00E+01
A2:SQUARE PULSE FROM 0.5 TO 1.0 SEC
FREQRESP-BODE
0 0 $0
000072-000000
110782-163012

Figure 29

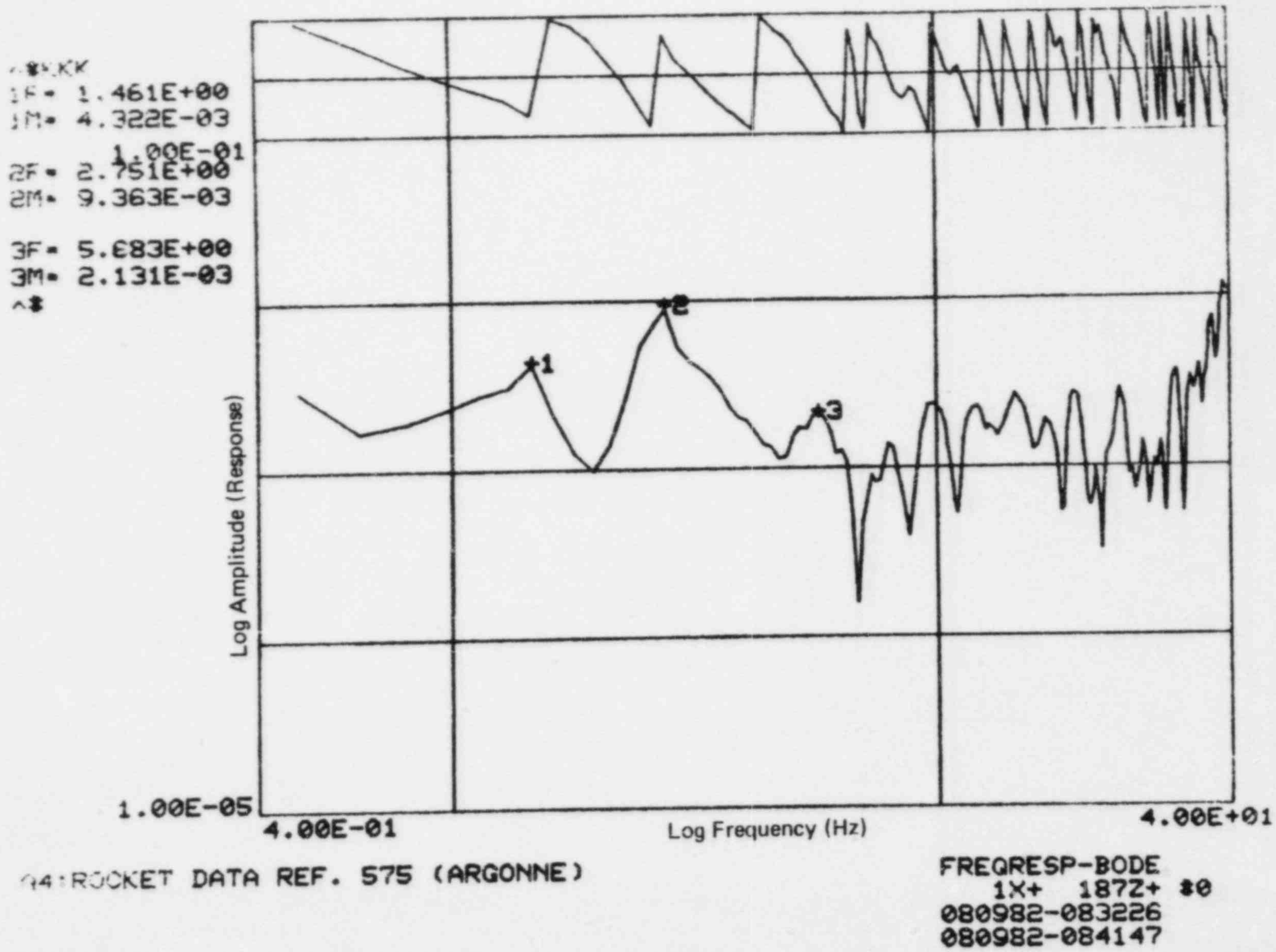


Figure 30
Response Spectrum at Point 187Z
Due to the Rocket Blast

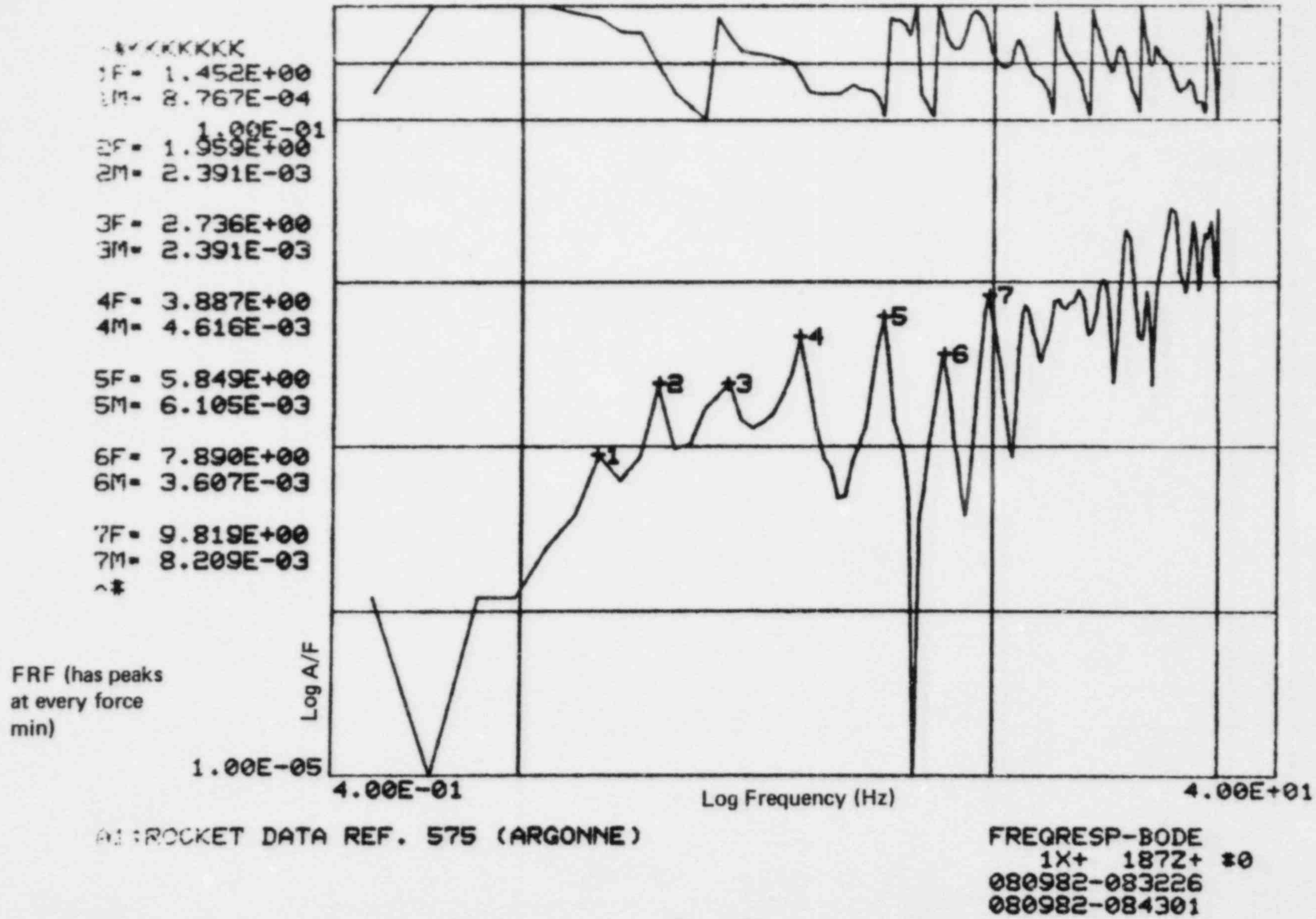


Figure 31
FRF from Rocket Data (for response point 187Z)

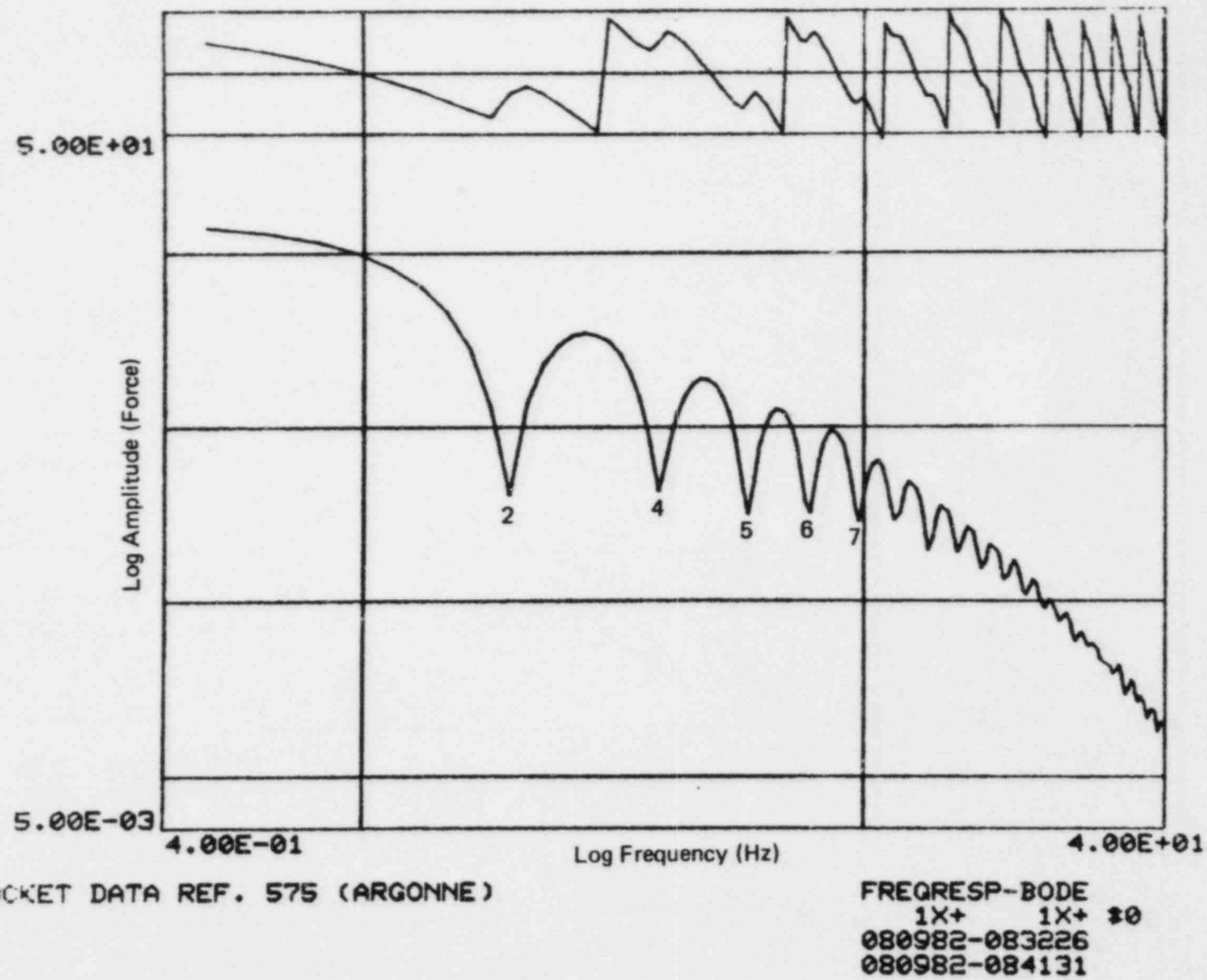


Figure 32
Force Spectrum of the Rocket Input

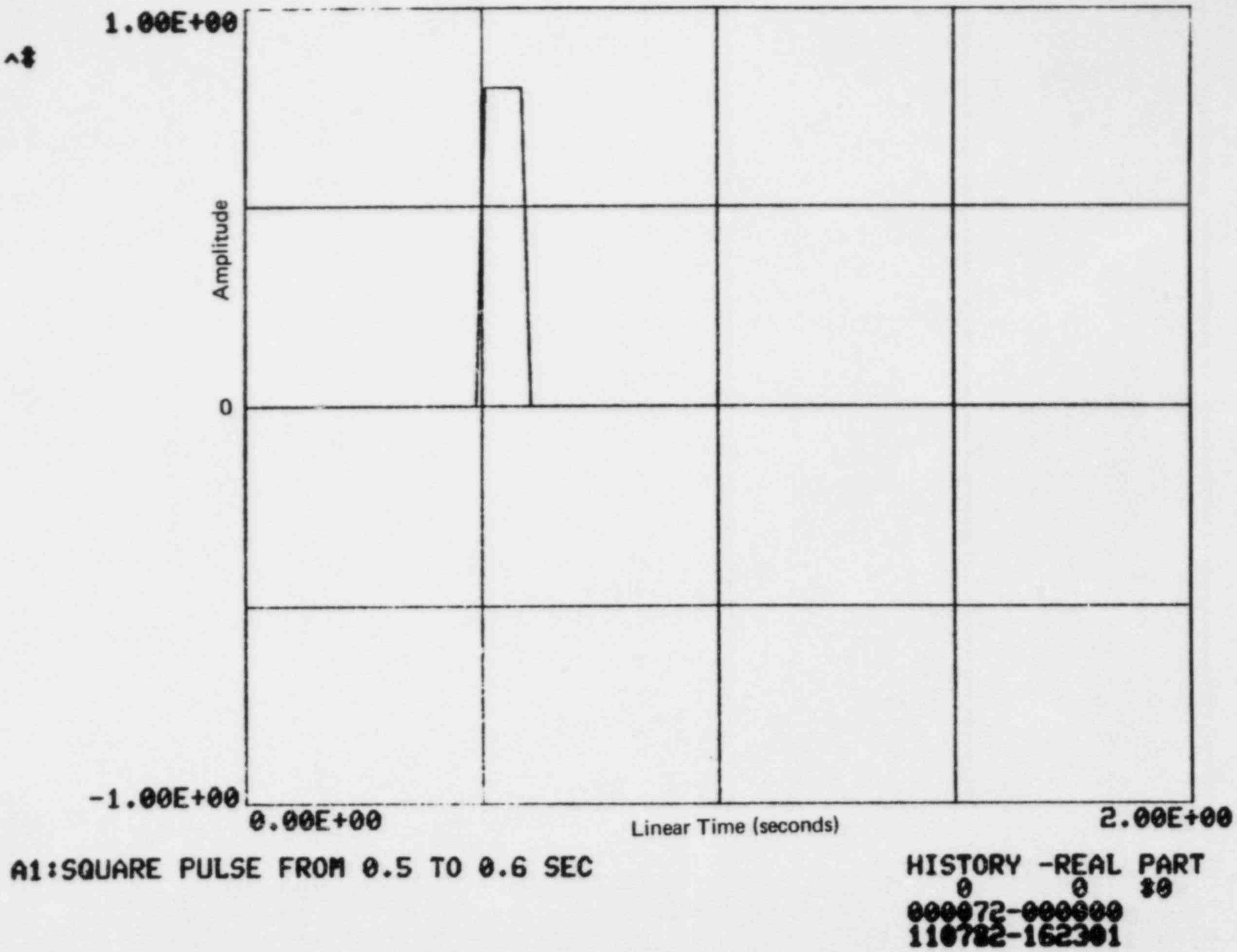


Figure 33
Mathematically Generated Pulse that is 0.1 Second Long

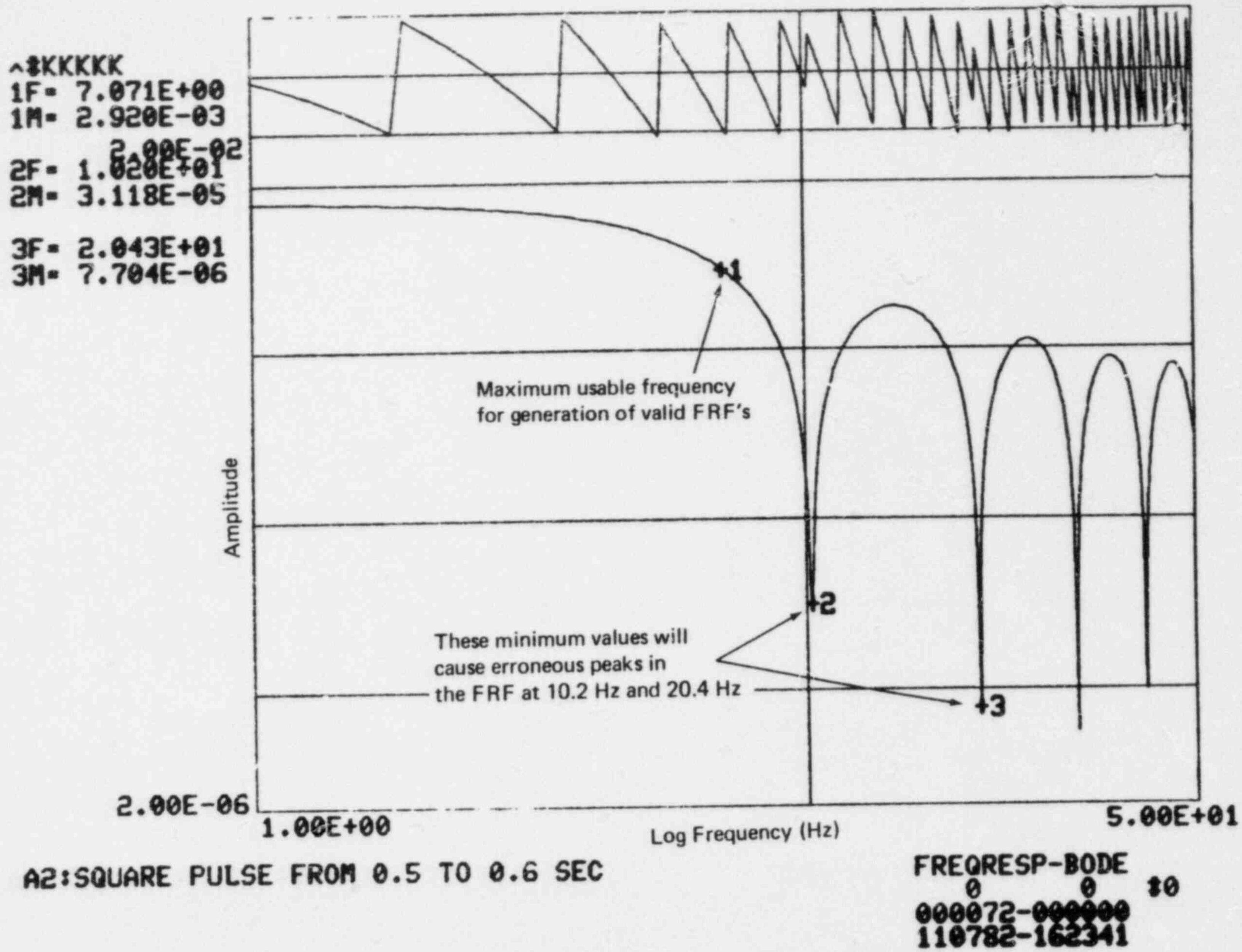


Figure 34
Spectra of a 0.1 Second Pulse

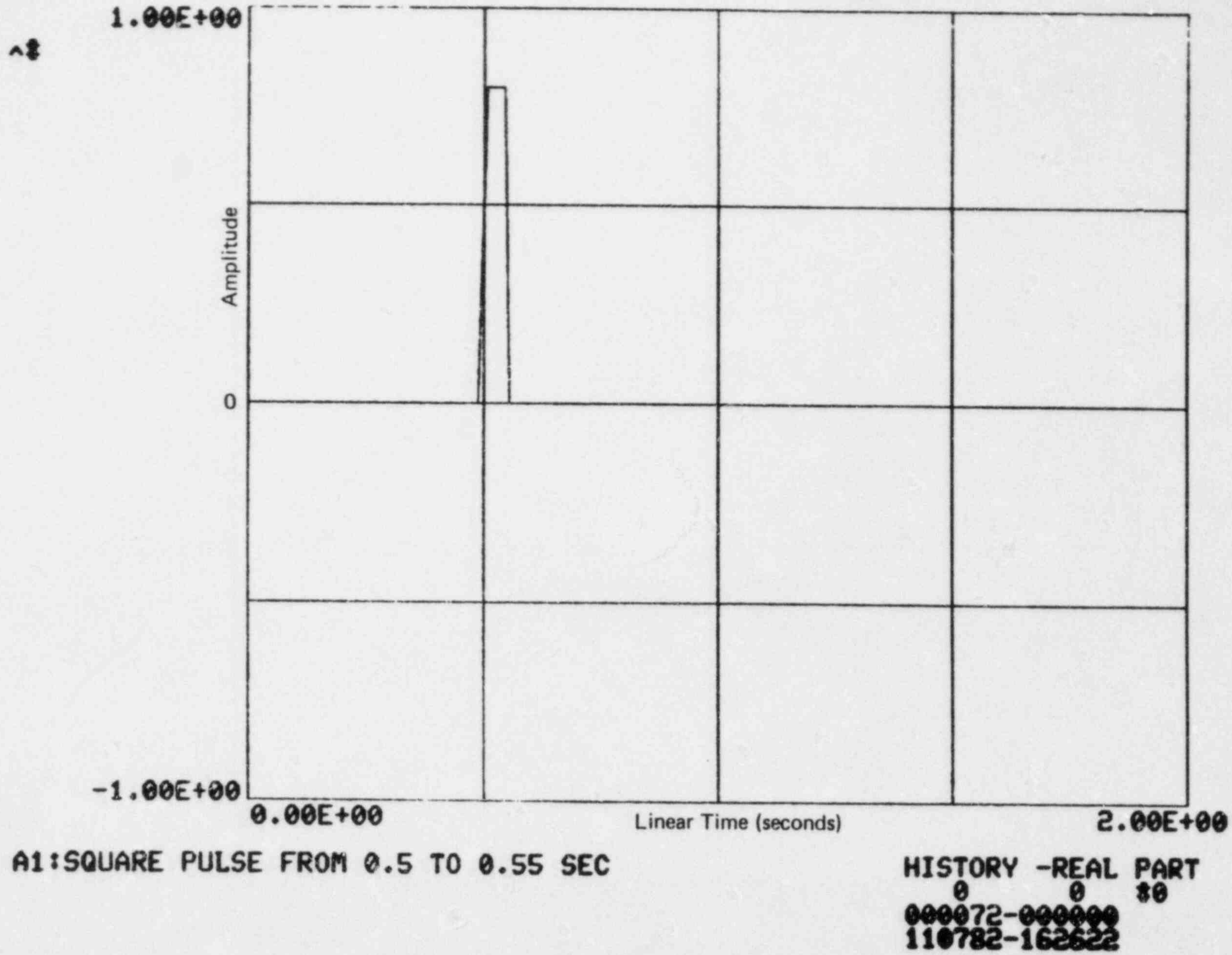


Figure 35
Mathematically Generated Pulse that is 0.05 Second Long

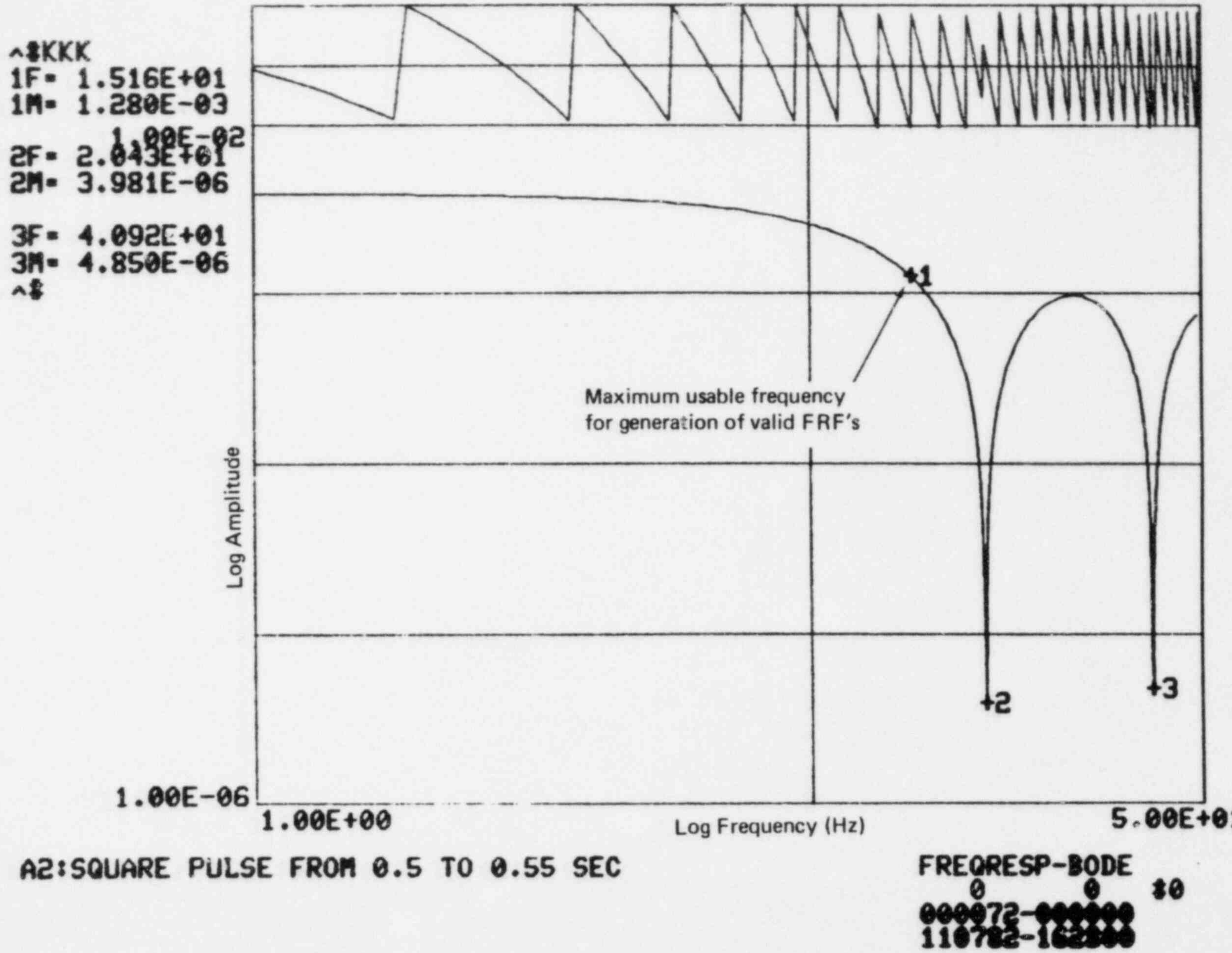


Figure 36
Spectra of a 0.05 Second Pulse

II.3 EXPLOSION TESTS

There was no direct measurement of the force that was generated during the explosion test. This measurement of course cannot be made directly. The explosion data was, therefore, only going to be used to test out the other models by applying some broadband spectrum to them at ground level and seeing if the predicted response was similar to that measured from the explosion data. Since the rotating mass exciter data and the rocket data failed to result in meaningful models, the explosion data was not used at all.

II.4 SABBA MODEL

Since part of the goal of this project was to show Argonne how SABBA worked, it was decided to make one SABBA model with the 4 modes from the dual rotating mass exciter. This model is, of course, so limited as to be practically worthless but it does demonstrate how SABBA uses the data passed to it by MODAL-PLUS.

Figure 37 shows the filenames, and documents the parameter file for the 4 modes (damped natural frequency, equivalent viscous damping ratio, amplitude of the residue for the given reference and response locations, etc.).

Figures 38-41 document the mode shape amplitudes (these amplitudes are not scaled to a maximum of 1.0 so there is no round off problem like occurred in Figures 9, 11, 13 and 15).

Figure 42 is the interactive input from the SABMOD run that created the SABBA input file shown in Figure 43.

Figures 44 and 45 show the interactive SABBA run. Figures 46-50 are output by SABBA to be used by the analyst to check the set-up. The run requested a forced response with a sinusoidally varying frequency from 1 to 5 Hz (the "valid" range of the model). The amplitude chosen for the force input was unity. We have therefore, requested an analytical run that should compare with the experimental data collected while using the dual rotating mass exciters.

The comparisom of the analytical prediction (Figure 51) from SABBA and the experimentally obtained FRF (Figure 52) was quite reasonable.

```
?Z

Z ARGONZ
  072982-144832   0/ARGONNE 11340-1-112
P ARGONP
  021082-143412   5/ARGONNE 11340-1-112
S ARGONS
  110382-140527   4/MASTER MODE SHAPE FILE
G ARGONG
  081082-132305   1/ARGONNE 11340-1-112
H ARGONH2
  080582-090923 400/CORRECTED ARGONH1 A/F W PROPER ME
T ARGONT1
  100482-193048  40/ARGONNE
*RP1;LP
MODE PARAMETERS
LABEL   FREQ   DAMPING  AMPLITUDE   PHASE   REF    RES  MODE   FLAGS
  1     1.481  0.04130  2.1281E-04  1.571  533X+  33X+   1   0 0 0 1 1
  2     1.534  0.04727  3.3492E-04  1.571  533Z+  33Z+   2   0 0 0 1 1
  3     2.538  0.03584  1.1519E-04  1.571  533X+  33X+   3   0 0 0 1 1
  4     2.682  0.03848  1.5414E-04  1.571  533Z+  33Z+   4   0 0 0 1 1
*FS
S RECORDS IN USE
REC 1:       1.481 HZ
REC 2:       1.534 HZ
REC 3:       2.538 HZ
REC 4:       2.682 HZ
*
```

Figure 37

```
PG1
*PC
MODE SHAPE 1: 533X+ A/F    REAL, FREQ =      1.481 HZ
*LS
MODE SHAPE
```

LOC	X COEFF	Y COEFF	Z COEFF
15	0.0000E+00	0.0000E+00	0.0000E+00
16	0.0000E+00	0.0000E+00	0.0000E+00
17	0.0000E+00	0.0000E+00	-1.2642E-05
27	0.0000E+00	0.0000E+00	3.0007E-05
28	0.0000E+00	0.0000E+00	4.1624E-05
33	5.5437E-04	-5.0151E-05	1.9171E-05
34	5.5228E-04	0.0000E+00	0.0000E+00
35	5.6900E-04	0.0000E+00	0.0000E+00
100	1.8978E-04	0.0000E+00	4.2892E-06
128	9.6394E-05	0.0000E+00	5.0706E-06
146	2.1467E-04	0.0000E+00	-3.9992E-05
167	3.0735E-04	0.0000E+00	-1.0216E-04
175	4.5736E-04	0.0000E+00	5.2200E-05
187	5.3598E-04	0.0000E+00	-1.8060E-05
197	0.0000E+00	6.1681E-05	-1.5212E-05
198	2.6569E-05	8.3179E-06	0.0000E+00
199	0.0000E+00	-6.7516E-05	0.0000E+00
201	3.1935E-05	-3.8724E-06	-8.6826E-07
303	3.6154E-05	0.0000E+00	0.0000E+00
533	0.0000E+00	0.0000E+00	0.0000E+00

```
*
```

Figure 38

~S2
$PS
MODE SHAPE 2: 533Z+ A/F   REAL, FREQ =   1.534 HZ
$LS
MODE SHAPE

LOC	X COEFF	Y COEFF	Z COEFF
15	-1.1433E-04	2.4337E-05	0.0000E+00
16	-2.4808E-05	0.0000E+00	0.0000E+00
17	0.0000E+00	0.0000E+00	6.3603E-04
27	0.0000E+00	0.0000E+00	5.3095E-04
28	0.0000E+00	0.0000E+00	5.0821E-04
33	-5.4478E-05	-4.9055E-05	7.3430E-04
34	-1.1227E-05	0.0000E+00	0.0000E+00
35	-1.6673E-05	0.0000E+00	0.0000E+00
100	-7.1711E-07	0.0000E+00	1.6133E-04
128	-4.9301E-07	0.0000E+00	5.4344E-05
146	2.3485E-05	0.0000E+00	1.7390E-04
167	8.5403E-05	0.0000E+00	2.6553E-04
175	-5.3066E-05	0.0000E+00	3.4475E-04
187	-1.0084E-06	0.0000E+00	4.1335E-04
197	0.0000E+00	1.3468E-05	2.2275E-05
198	-7.3952E-07	5.1968E-05	0.0000E+00
199	0.0000E+00	1.9496E-06	0.0000E+00
201	-4.8181E-06	-3.0925E-06	2.6712E-05
303	-2.0393E-06	0.0000E+00	0.0000E+00
533	0.0000E+00	0.0000E+00	0.0000E+00

$

Figure 39

MS3
$PS
MODE SHAPE 3: 533X+ A/F   REAL, FREQ =   2.538 HZ
$LS
MODE SHAPE

LOC	X COEFF	Y COEFF	Z COEFF
15	0.0000E+00	0.0000E+00	0.0000E+00
16	0.0000E+00	0.0000E+00	0.0000E+00
17	0.0000E+00	0.0000E+00	1.2720E-04
27	0.0000E+00	0.0000E+00	1.2657E-04
28	0.0000E+00	0.0000E+00	1.1563E-04
33	2.0234E-04	-3.5483E-05	1.5697E-04
34	2.0720E-04	0.0000E+00	0.0000E+00
35	2.3052E-04	0.0000E+00	0.0000E+00
100	4.9210E-05	0.0000E+00	2.2449E-05
128	-3.9716E-05	0.0000E+00	-1.4973E-05
146	-1.6397E-04	0.0000E+00	-5.0199E-05
167	-3.0015E-04	0.0000E+00	-8.0995E-05
175	-4.9087E-04	0.0000E+00	-2.8141E-04
187	-6.4810E-04	0.0000E+00	-2.6923E-04
197	0.0000E+00	-4.1694E-05	-3.7580E-07
198	-1.5428E-06	-1.7445E-05	0.0000E+00
199	0.0000E+00	3.1805E-05	0.0000E+00
201	-1.0681E-06	-3.4613E-06	-1.3845E-07
303	-1.6614E-06	0.0000E+00	0.0000E+00
533	0.0000E+00	0.0000E+00	0.0000E+00

$

Figure 40

#PS4
#PS
MODE SHAPE 4: 533Z+ A/F   REAL, FREQ =   2.582 HZ
#LS
MODE SHAPE

LOC	X COEFF	Y COEFF	Z COEFF
15	-4.4634E-05	1.7497E-05	0.0000E+00
16	-1.7235E-05	0.0000E+00	0.0000E+00
17	0.0000E+00	0.0000E+00	2.1134E-04
27	0.0000E+00	0.0000E+00	1.8293E-04
28	0.0000E+00	0.0000E+00	1.7541E-04
33	-1.7723E-05	-4.3697E-06	2.3750E-04
34	-4.6697E-06	0.0000E+00	0.0000E+00
35	-5.6825E-06	0.0000E+00	0.0000E+00
100	2.3067E-06	0.0000E+00	3.1901E-05
128	-3.7508E-07	0.0000E+00	-2.8619E-05
146	-1.4872E-05	0.0000E+00	-1.6798E-04
167	-8.6381E-05	0.0000E+00	-3.0697E-04
175	1.0163E-04	0.0000E+00	-4.7534E-04
187	1.5134E-05	0.0000E+00	-6.1451E-04
197	0.0000E+00	-1.1046E-05	-4.2384E-06
198	-2.6256E-07	-2.6443E-05	0.0000E+00
199	0.0000E+00	-4.6322E-06	0.0000E+00
201	-8.0642E-07	5.5324E-06	-4.2384E-06
303	-7.6891E-07	0.0000E+00	0.0000E+00
533	0.0000E+00	0.0000E+00	0.0000E+00

#

Figure 41

```
SABMOD
                 S A B M O D
   SABBA - MODAL-PLUS INTERFACE PROGRAM
                VERSION  4.01
                 01-NOV-81
ENTER:
      1  TO GENERATE SABBA  INPUT DATA
      2  TO EDIT SABBA  INPUT DATA
      KI TO EXIT SABMOD
:1
ENTER SABBA INPUT    FILE NAME:
:ARGSABIINP^R
ARGSAB.INP
ENTER SYSTEM TITLE (UP TO 72 CHARACTERS)
:ARGONNE'S GERMAN HDR MODEL-- 1 TO 5 HZ
ENTER:
      0  TO RETURN TO THE MASTER PROMPT
      1  TO GENERATE A MODAL COMPONENT
      2  TO GENERATE SCALAR ELEMENTS
      3  TO GENERATE SINUSOIDAL LOAD DATA
:1
ENTER:
      1  FOR VISCOUS DAMPING
      2  FOR HYSTERETIC DAMPING
:1
 ENTER:
       1 FOR STIFFNESS FORMULATION
       2 FOR MODAL     FORMULATION
:1
ENTER:
      0 FOR NO COMPONENT LOADS CALCULATED
      1 FOR ALL COMPONENT LOADS CALCULATED
:0
```

Note: User responses are underlined

Figure 42

```
TYPE ARGSAB.INP
100,SYSTEM
110,ARGONNE'S GERMAN HDR MODEL-- 1 TO 5 HZ
120,MODAL,1,0,S,V
130,DATA FROM DUAL ROTATING UNBALANCE EXCITERS
140,FDOF
150,33X,33Z,175X,175Z
160,FREQ
170,1.481,1.534,2.538,2.682
180,MASS
190,0.2186E+05,0.1439E+05,0.6922E+05,0.5467E+05
200,DAMP
210,0.041,0.047,0.036,0.038
220,DISPLACEMENT
230,1.000,-0.074,1.000,-0.075
240,0.035,1.000,0.776,1.000
250,0.825,-0.072,-2.426,0.428
260,0.094,0.469,-1.391,-2.002
270,LOAD
280,UNIT AMPL.,SINUS. FORCE FROM 1 TO 5 HZ
290,SINUSOIDAL
300,,FORCE,33X,1.000,0.000
$
```

Figure 43

```
S A B B A

SYSTEM ANALYSIS  -  BUILDING BLOCK APPROACH

STRUCTURAL DYNAMICS RESEARCH CORPORATION

VERSION  4.01   01-NOV-81

ENTER TERMINAL DESIGNATION
     1  FOR TEKTRONIX 4012
     2  FOR TEKTRONIX 4014
     3  FOR TELETYPEWRITER
     4  FOR GEN RAD 2508
? 1

AUTOMATIC HARD COPY (Y/N)
? Y

ENTER MASTER DATA FILE NAME
? ARGSAB.INP

ENTER SOLUTION CODE
     1  FOR NATURAL FREQUENCY AND MODE
     2  FOR FORCED RESPONSE
? 2
```

Figure 44

```
ENTER INPUT DATA PRINT CODE
     0  FOR NONE
     1  FOR INTERACTIVE
     2  FOR FILE
? 1

DISPLAY SYSTEM MATRIX (Y/N)
? Y

ENTER FREQUENCIES (F1, F2, NF)
? 1,5,20

ENTER SABBA OUTPUT FILE NAME
? ARGSAB.OUT

OK FOR NEW FILE -ARGSAB.OUT


(Y/N)
? Y
```

Figure 45

S A B B A

SYSTEM ANALYSIS - BUILDING BLOCK APPROACH

STRUCTURAL DYNAMICS RESEARCH CORPORATION
ARGONNE'S GERMAN HDR MODEL-- 1 TO 5 HZ

---MODAL SUPERPOSITION---

COMPONENT NUMBER 1

DATA FROM DUAL ROTATING UNBALANCE EXCITERS

FREE DEGREES OF FREEDOM

1/33X	2/33Z	3/175X	4/175Z

DAMPING TYPE : VISCOUS
DAMPING PROPORTIONALITY : PROPORTIONAL
REQUESTED FORMULATION : STIFFNESS

Figure 46

SYSTEM ANALYSIS - BUILDING BLOCK APPROACH
ARGONNE'S GERMAN HDR MODEL-- 1 TO 5 HZ

MODE	NATURAL FREQUENCY	MODAL MASS	MODAL DAMPING
1	1.48100E+00	2.18600E+04	4.10000E-02
2	1.53400E+00	1.43900E+04	4.70000E-02
3	2.53800E+00	6.92200E+04	3.60000E-02
4	2.68200E+00	5.46700E+04	3.80000E-02

MODAL DISPLACEMENT MATRIX

DOF	MODE 1	2	3	4
1	1.000E+00	-7.400E-02	1.000E+00	-7.500E-02
2	3.500E-02	1.000E+00	7.760E-01	1.000E+00
3	8.250E-01	-7.200E-02	-2.426E+00	4.280E-01
4	9.400E-02	4.690E-01	-1.391E+00	-2.002E+00

Figure 47

SYSTEM ANALYSIS - BUILDING BLOCK APPROACH
ARGONNE'S GERMAN HDR MODEL-- 1 TO 5 HZ

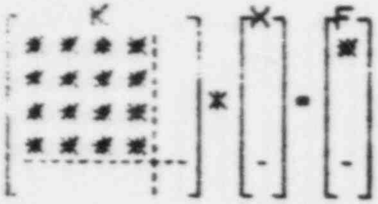
---SINUSOIDAL LOAD DATA---

UNIT AMPL.,SINUS. FORCE FROM 1 TO 5 HZ

COORDINATE	TYPE	AMPLITUDE	PHASE
33X	FORCE	1.000E+00	0.0

Figure 48

```
**** + **** SABBA SYSTEM SUMMARY **** + ****
ARGONNE'S GERMAN HDR MODEL-- 1 TO 5 HZ
```



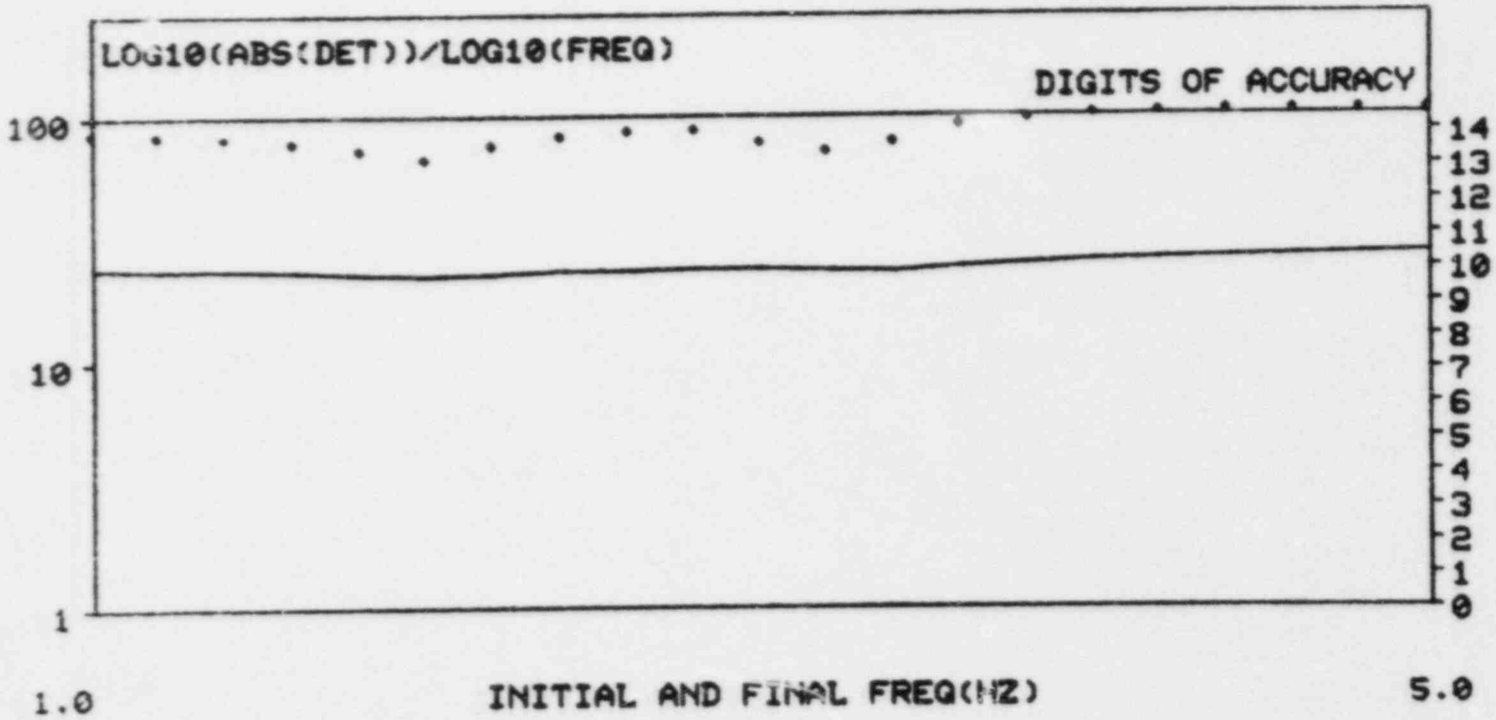
```
        MATRIX PARTITIONS                  COMPONENT FILE = ARGSAB.INP
NO SIZE         DESCRIPTION                     LOAD FILE = ARGSAB.INP
 1   0    INDEP. CONSTRAINT DOF            EXECUTION FILE =
 2   4    DOF NOT IN A CONSTRAINT             OUTPUT FILE = ARGSAB.OUT
 3   0    DEPENDENT CONSTRAINT DOF            MEMORY USAGE - INPUT=.00,EXEC=.00
 4   0    SPEC. DOF NOT CONSTR.            ANALYSIS=SINUSOIDAL, FREQ. STEPS=21
 5   0    SPEC. INDEP. CONSTR. DOF         F0(HZ)=1.00E+00, FN(HZ)=5.00E+00
 6   1    DOF = 0.0 (B.C.)

* COMPONENTS *
ID TYPE SIZE F            **** PHYSICAL DOF IN MATRIX ORDER ****
 1 MODL  4       33X       33Z       175X      175Z      GROUND
```

Figure 49

SABBA EXECUTION HISTORY   TIME 16:02:35   DATE 3-NOV-82

ARGONNE'S GERMAN HDR MODEL-- 1 TO 5 HZ

ANALYSIS TYPE = SINUSOIDAL
COMPONENT FILE = ARGSAB.INP   LOAD FILE = ARGSAB.INP
EXECUTION FILE =   OUTPUT FILE = ARGSAB.OUT



EXECUTION COMPLETE, NUMBER OF FREQUENCY STEPS = 21

Figure 50

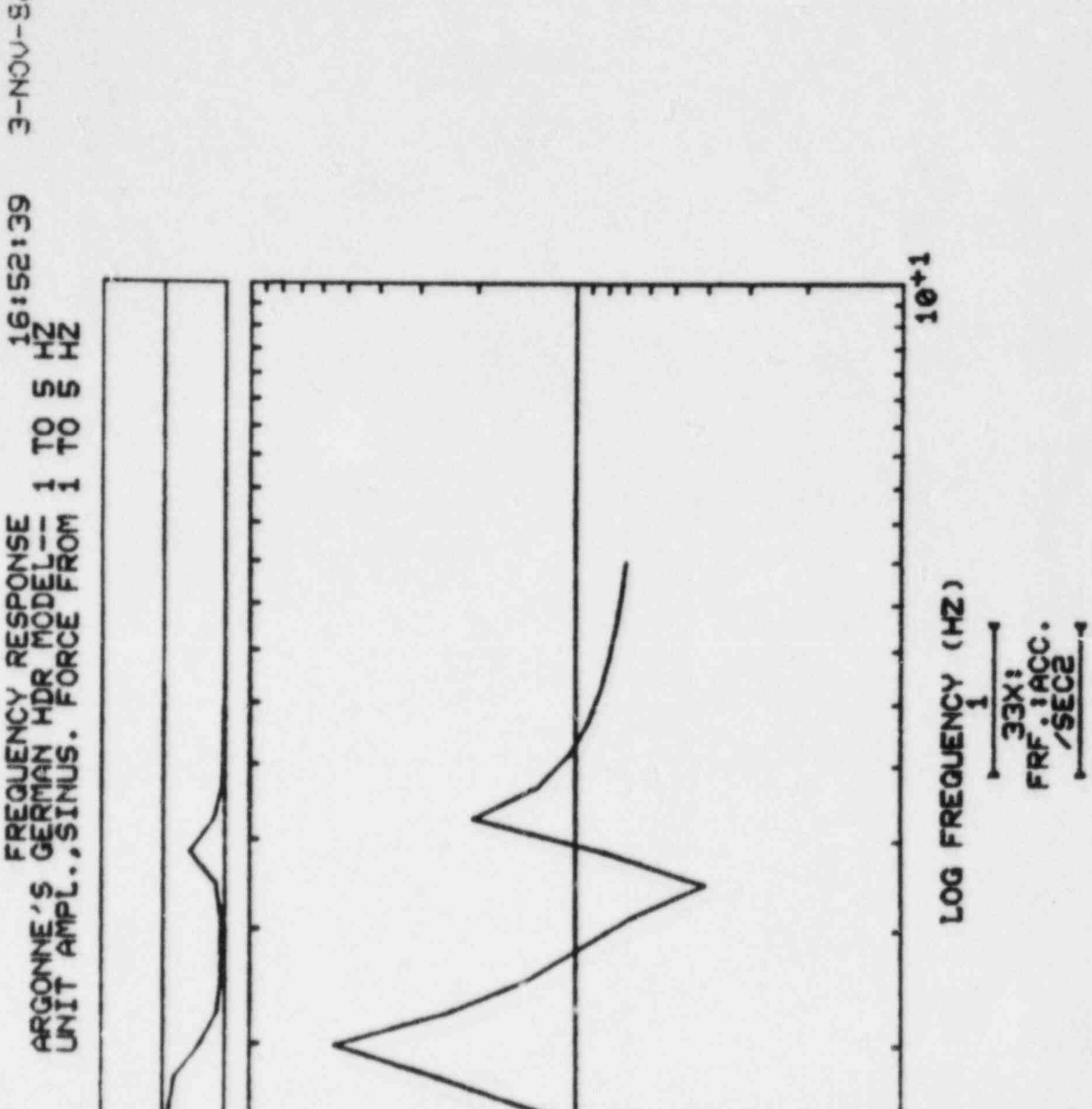

FREQUENCY RESPONSE
ARGONNE'S GERMAN HDR MODEL-- 1 TO 5 HZ
UNIT AMPL.,SINUS. FORCE FROM 1 TO 5 HZ
16:52:39
3-NOV-82
0
-180
-360
10-3
10-4
10-5
10+0
10+1
LOG FREQUENCY (HZ)
1
33X:
FRF.:ACC.
/SEC2

Figure 51

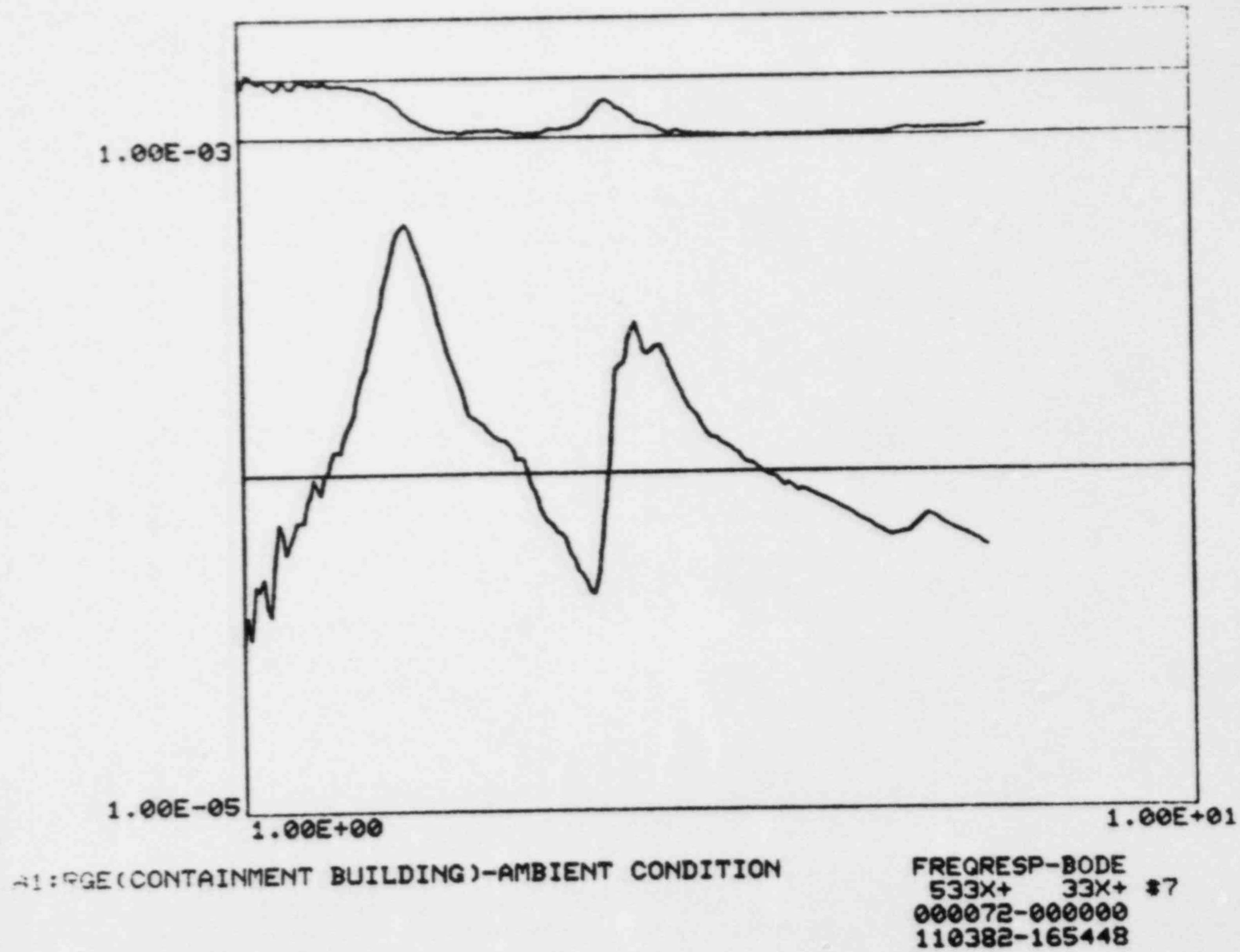

1.00E-03
1.00E-05
1.00E+00
1.00E+01
A1:RGE(CONTAINMENT BUILDING)-AMBIENT CONDITION
FREQRESP-BODE
533X+ 33X+ $7
000072-000000
110382-165448

Figure 52

Distribution for NUREG/CR-4021 (ANL-84-25)

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13. ABSTRACT (200 words or less)

An attempt to verify the reliability of the experimental modal modeling code, MODAL-PLUS, is described in this report. MODAL-PLUS is capable of synthesizing a modal model of a structure using data from dynamic testing of a structure. The objective was to determine whether a modal model synthesized from one set of test data would be capable of correctly predicting response to a different form of excitation from a different set of data. Recorded test data from the shaker and rocket tests on the containment building of the HDR (Heissdampfreaktor) were used in the effort. The attempted verification was only partially successful in that only one modal model with a limited range of validity could be synthesized from the shaker test data. The goodness of fit in this limited range was adequate. The rocket test data could not be used to synthesize a modal model due to numerical difficulties. However, the effort was useful in showing the need for taking into account the possible use of the data, and the data analysis method to be employed, at an early stage when the tests are being designed.

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