Integrated Dynamic Test/Analysis Processor Overview

By

Robert N. Coppolino
Branch Manager
The MacNeal-Schwendler Corporation

ABSTRACT

A new system which provides integrated dynamic testing and mathematical model analysis capability is described. The integrated system addresses four key tasks, namely, (1) pretest planning and analysis, (2) test data acquisition, (3) data reduction and analysis, and (4) test/analysis correlation and mathematical model updates. Several key software programs are employed to accomplish this task. They are MSC/NASTRAN, MSC/STI-VAMP and MSC/GRASP, along with appropriate interface utilities. A simple tower structure is used to illustrate operation of the integrated test analysis processor.

INTRODUCTION

During the past fifteen years, the structural sciences have enjoyed great advances in both analytical and experimental applications. Powerful finite-element programs such as MSC/NASTRAN(1) generate realistic predictions of structural responses to a variety of stimuli with ease and precision. Recent emphasis on new laboratory techniques has produced a number of excitation, measurement, and analysis methods that promptly and effectively estimate pertinent dynamic parameters of both simple and complex structural systems.

Test and analysis methods are frequently combined in the development of a test-verified model. When it is impossible or impractical to simulate an expected dynamic environment, an accepted analysis procedure is to use the test verified mathematical model to evaluate the subject structure's performance in that environment. The experimental phase (modal test) is greatly expedited by thorough pre-test analysis and rapid assessment of test results with online test-support analyses. The primary objective of the post-test analysis is to verify and/or refine the behavior of the finite-element model.

While the test and analysis functions have experienced significant improvements in the last few years, little has happened to improve the analytical/experimental interface. The model-refinement process is not yet a systematic, objective procedure. Experience has shown this step to be the most time-consuming element in the development of a test-verified model.

This paper presents an approach to modal testing that establishes an efficient interface between calculated and measured results. That interface is exploited to hasten the accurate determination of a test-verified model. The process begins with systematic test planning using finite-element models.Test-support analyses are used to help assure adequacy and completeness of measured data. This online activity, combined with a test system that offers alternative test techniques, provides the best opportunity to achieve satisfactory results. Finally, a systematic procedure which guides refinement of the finite-element model is used.

The Integrated Dynamic Testing and Analysis Concept

Integrated testing and analysis viewed in Figure 1 is a process which follows key milestones in the system development cycle. The general approach was pioneered mainly in the aerospace industry with defense related organizations defining the most demanding goals and strictest criteria(2). Since the 1970's modern industry as a whole has steadily increased its committment to systematic vibration mode testing (termed modal analysis). "ITAP", the integrated test/analysis process for dynamic systems incorporates well-coordinated activities in related technical disciplines, namely,

(1) Mathematical modeling and analysis principally by the finite element method (FEM).

(2) Measurement and analysis of excitation and response data (signal analysis).

(3) Identification of test article parameters (e.g. modes, natural frequencies, damping) from experimentally determined signals and signatures.

(4) System identification principally aimed at reconciliation of mathematical models and test deduced information.

ITAP is automated by the use of advanced hardware systems for data acquisition* and processing, and by several software packages. The primary software employed in ITAP is MSC/NASTRAN, MSC/STI-VAMP and MSC/GRASP. Communication among the three packages is presently accomplished by a mature data base system as well as NASVMP, a facility which interfaces test and analysis data bases.

Signal Analysis

MSC/STI-VAMP includes extensive capability to acquire (with the STI/DAAS option) and process sinusoidal, random and transient signals(3). These capabilities include FFT, auto- and cross-spectrum, shock spectrum, frequency response functions and coherence, as well as an extensive variety of general mathematical utilities and graphic displays. All of these capabilities are invoked by the use of two letter commands (sometimes followed by specific parameters).

Under the guidance of Dr. Julius S. Bendat, an authority in measurement and analysis of random data, upgrades to these capabilities as well as extensions to the command library have recently been implemented. The additions to the signal analysis library include probability analysis (also termed amplitude domain analysis)(4), Hilbert transform and envelope function calculation(5), and auto- and cross-correlation function calculation.

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* For example, STI/DAAS, a sophisticated data acquisition/analysis system offered by Synergistic Technology Incorporated.

Probability density and Hilbert transform functions are key capabilities for classification and study of non-linear operations. Examples of experimentally determined probability densities for a large rocket stage vehicle are provided in Figure 2. The first of these (Figure 2a) represents a random excitation which is predominately Gaussian. In contrast, the response probability density shown in Figure 2b is skewed with respect to the ideal Gaussian distribution (dotted curve) indicating the presence of bi-linear structural behavior.

An alternative method of detecting the presence of nonlinearity is based on the use of Hilbert transforms. Figure 3a exhibits linear system behavior due to close comparison of a measured frequency response function (real-imaginary display) with an associated Hilbert transformation (dotted curve) based function. In contrast the measured frequency response and associated Hilbert transform-based functions, shown in the magnitude-phase plot in Figure 3b, differ significantly indicating the presence of nonlinearity. Organized non-linear system analysis from measured data is at present beyond the capability of most commercially available packages.

MSC/STI-VAMP Version 7 will soon provide for straightforward multi input/multi output (MI/MO) signal analysis(4). MI/MO is a general purpose capability which is useful in empirical identification of sources of excitation as well as generalized input-output paths and relationships for structural, acoustic or any other dynamically responding systems.

Pre-Test Planning with Mathematical Models

The role of the mathematical modeling and analysis in the ITAP effort for structural systems begins during the test planning exercise. The most up-to-date version of the mathematical model is employed to scope the approximate number of modes to be sought, identify candidate exciter locations and configurations, and determine an appropirate accelerometer array. Experience has taught the MSC/STI team that pre-test FEM analysis, which includes parameter sensitivity studies, is often vital to the success of the ITAP effort. In response to the requirements for adequate pre-test evaluations an MSC/NASTRAN based procedure (MODPREP) has been developed to formalize the FEM based test planning task. The MODPREP procedure asseses the adequacy of candidate accelerometer arrays (which correspond to the analysis-set of a Guyan reduced model) by mathematical comparison of reduced model modes with subspace iterated modes via cross-orthogonality. The predicted system modes are displayed and categorized with modal effective mass, mode displacement, momentum and kinetic energy distribution tables as well as MSC/GRASP animated and frozen modal displays. If appropriate, modal stress contours may also be displayed with MSC/GRASP. The function of the tabular data is to provide systematic information to identify the direction and locations of dominant modal activity.

Using the four bay tower illustrated in Figure 4, a FEM analysis was performed to assess the adequacy of an accelerometer array for measurement of lateral "Y" modes in that direction. Pre-test analysis indicates that accelerometers at grid point/dof locations 1Y, 2Y, 5Y, 6Y, 9Y, 10Y, 13Y, 14Y, and 21Y adequately characterize predicted behavior of this structure on the basis of natural frequency (Table 1), cross-orthogonality and orthogonality data computed in MODPREP. Overall character of the predicted modes is summarized in the modal effective mass display given in Table 2. More detailed modal information is provided in modal vector tables (Table 3) and mode shape plots (Figure 5), respectively, illustrating the tower's predicted second lateral mode.

The pre-test information is available for comparison with experimentally determined modes through the NASVMP interface utility. This interface is capable of transmitting information from laboratory computers to the finite-element host computer if different, and vice-versa. Sufficient generality exists in NASVMP to communicate among a wide variety of computer systems.

Modal Analysis

The term "modal analysis" in the last decade has become accepted jargon for experimental modal testing and data reduction. MSC/STI-VAMP includes processing algorithms to estimate structural dynamic natural frequencies, damping and mode shapes from measured frequency response functions. The procedures employed in the "FITTER" algorithms consist of single and multi-degree-of-freedom iterative curve fitters along with global skyline displays which assist the engineer in defining frequency bands of interest. FITTER is a mature portion of MSC/STI-VAMP which has been used in a variety of structural dynamic modal tests(6).

Recently a new, sophisticated modal analysis option has been added to MSC/STI-VAMP. The technique called Simultaneous Frequency Domain (SFD) was developed in 1980(7). It has been continually upgraded and employed on a variety of spacecraft and offshore structure mode tests since its introduction(8). The most recent applications of this technique have been on the Galileo and Centaur G-Prime modal tests. The SFD technique rapidly and reliably estimates modal parameters by processing the entire frequency response ensemble (all accelerometers) simultaneously. It first processes that data to determine the number of modes present (the system rank). As part of this process the information associated with all measurements is compressed into a small set of generalized frequency response functions. These functions along with a fixed vector set entirely describe the behavior of the test article. By the use of a linear least squares process effective dynamic system matrices are identified, from which vibration mode parameters are deduced. The entire SFD calculation is performed in a matter of minutes for a test article instrumented with well over 100 accelerometers. Results of the SFD calculation are displayed in tabular and graphical form which includes objective indicators of modal test data integrity.

In practice, modal analysis is best performed in several stages. These include preliminary quick-look evaluations(8,9), detailed mode identification with SFD and FITTER, and graphical reconstruction of measured data for assessment of identified modes. Employing the tower structure example, preliminary skyline functions developed in MSC/STI-VAMP (Figures 6 and 7) indicate the presence of four lateral modes in the 0-50 HZ frequency band which are well-excited by a load applied at location "21Y". Moreover, individual accelerometer frequency response function plots shown in Figure 8 (magnitude-phase for 0-50 HZ) and in Figure 9 in a narrower range are useful for quick-look evaluations.

Detailed identification of modal parameters from all measured response data is efficiently performed by SFD analysis in selected frequency bands. A variety of tabular and graphical displays are available to guide the analyst in performing on-line evaluation of the identification process. Among the displays are generalized frequency response functions which indicate dominant modal activity. The composite plot shown in Figure 10 clearly indicates single mode behavior of the tower structure in the 25-28 HZ range. It is interesting to note, upon comparison with the measured function in Figure 9, that the SFD based generalized frequency response tends to separate modal activity from noise. An additional property of SFD based generalized frequency response functions is illustrated in Figure 11 which exhibits multi-mode activity of a rocket stage vehicle test article in the 8.5-10.4 HZ range.

The final stage of modal analysis consists of a linear least-squares curve fit using FITTER over the entire frequency range of measured data. Employing the complete set of identified natural frequencies and damping values obtained from SFD, a global set of mode shapes and re-synthesized (fitted) frequency response functions is obtained. Tabular output from FITTER is illustrated for the second lateral mode of the tower in Table 4. Plots of global skylines based on measured and fitted response functions are illustrated in Figure 12 along with mode locations. Finally, comparison of individual measured re-synthesized frequency response functions, as shown in Figure 13, provide a high level of confidence in the identified modal parameters.

For MSC/STI-VAMP installations which include the STI/DAAS system, vibration modes may be optionally identified by multi-exciter tuning methods. Such methods, which originated in aircraft industry(10,11) rely on the ability of several shakers to sinusoidally excite an individual mode while suppressing modes at neighboring frequencies. Laboratory procedures to accomplish this objective were originally slow and tedious. With the introduction of digital computers to the laboratory, however, tuning procedures have become increasingly efficient. It is the philosophy of MSC/STI-VAMP that a relatively complete arsenal of modal identification techniques, based on numerical fitting and tuning approaches, offers the most promising opportunity for success in modal analysis.

Test/Analysis Correlation and Mathematical Model Updates

Once a sufficiently complete set of modal data is obtained this information must be systematically compared with pre-test FEM based data. Moreover, regions of the structural model requiring update along with the degree of update should be identified. The post-test evaluation process has been formalized in an MSC/NASTRAN based procedure (MODTEST). This procedure calculates orthogonality and cross-orthogonality of test modes with respect to the FEM based mass matrix in order to assess the quality of experimental modes and to logically compare test and FEM modal data. The experimental mode information is displayed and categorized like the FEM data in MODPREP with modal effective mass, mode displacement, momentum and kinetic energy distribution tables as well as animated and fixed modal displays. The MODTEST procedure computes on a mode-by-mode basis the "dynamic imbalance" between FEM matrices and experimental mode data to locate areas of discrepancy between the FEM and test article. Finally, employing an optimal analysis procedure(12) an updated test-based stiffness matrix is calculated and compared to the FEM pre-test stiffness. While this capability only provides information regarding reduced rather than complete FEM stiffness, it serves as an efficient guide to post-test FEM updates.

Continuing with the four bay tower example, the experimental mode data is translated with the NASVMP interface utility into an MSC/NASTRAN INPUTT4 file. This data is then processed with the MODTEST procedure. The test modes with natural frequencies and damping noted in Table 5 exhibit good orthogonality as evidenced by small off-diagonal terms in Table 6a. Moreover, cross-orthogonality of test modes with respect to pre-test analytical modes, presented in Table 6b, indicates that the respective mode shape sets compare closely even though the frequencies differ.

Character and content of the measured modes are illustrated in tabular and graphical form in Table 7 and Figure 14, respectively, for test mode number 2. The column denoting energy imbalance ("DENRA") indicates that the discrepancy between test and prediction may be due to stiffness differences in the lower tower bay. This conclusion is corroborated by the on-diagonal stiffness summary presented in Table 8.

Concluding Remarks

The integrated dynamic testing and analysis system described in this paper has been presented with emphasis on its application to the vibration mode survey process. By employment of MSC/NASTRAN, MSC/STI-VAMP, MSC/GRASP and interface utilities, a complete modal test/analysis process may be carried out.

Versatility of the integrated test/analysis system permits its application to a much wider class of applications than vibration mode surveys. Signal analysis capabilities in MSC/STI-VAMP may be employed in empirical system identification studies including source identification, nonlinearity identification and system health monitoring. The NASVMP interface may be used to facilitate tasks such as (a) generation of hybrid experimental/analytical component mode representations in MSC/NASTRAN and (b) interactive post-processing of FEM based dynamic models through calculation of response to transient and random environments in MSC/STI-VAMP.

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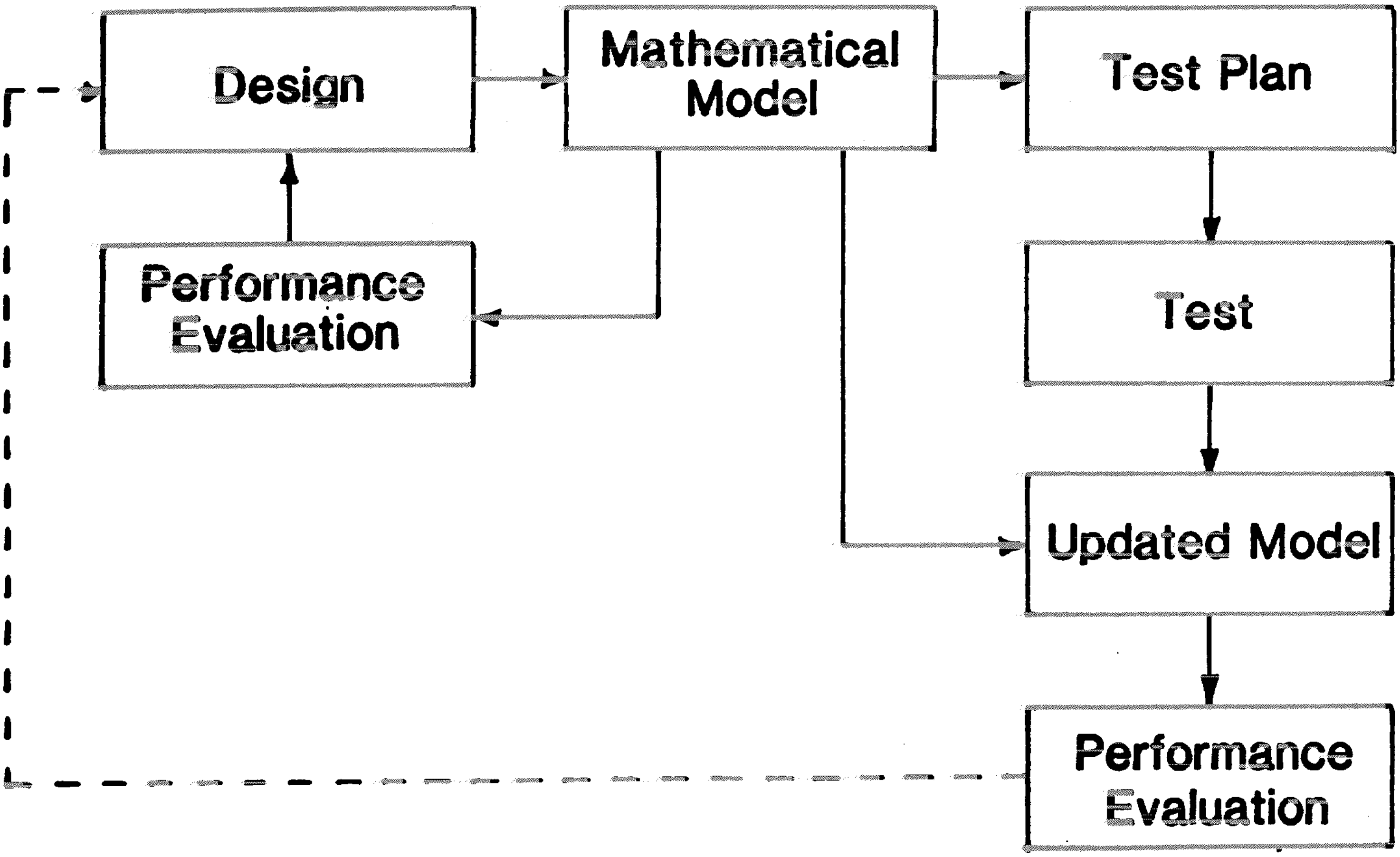
SYSTEM DEVELOPMENT CYCLE



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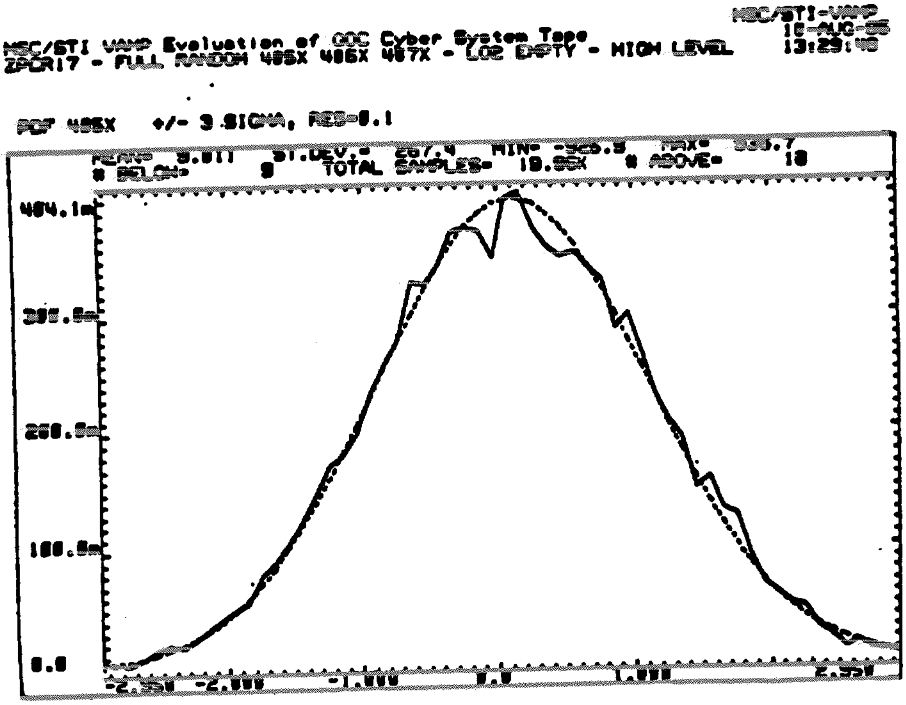

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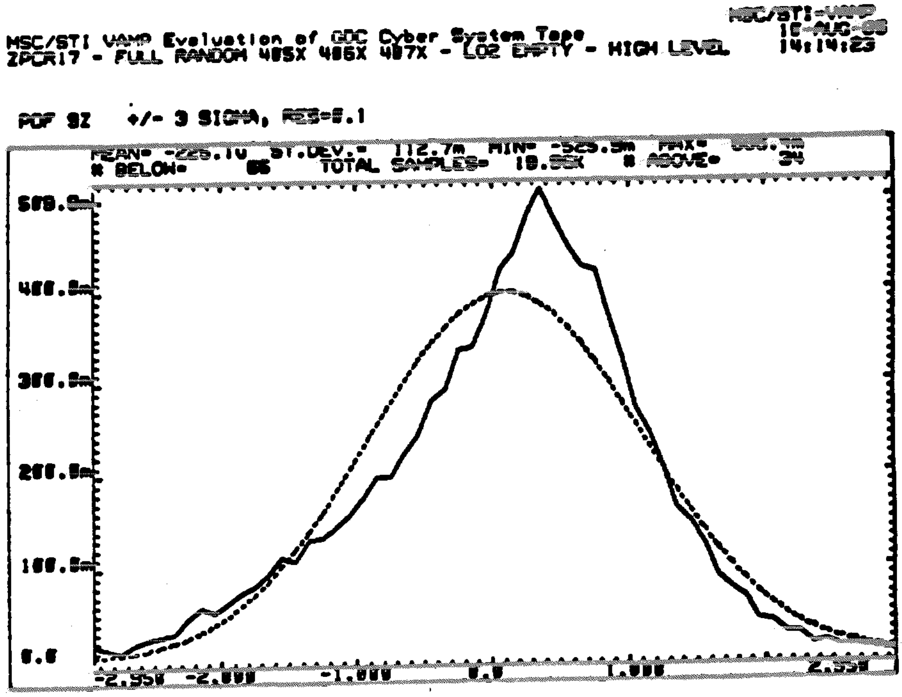

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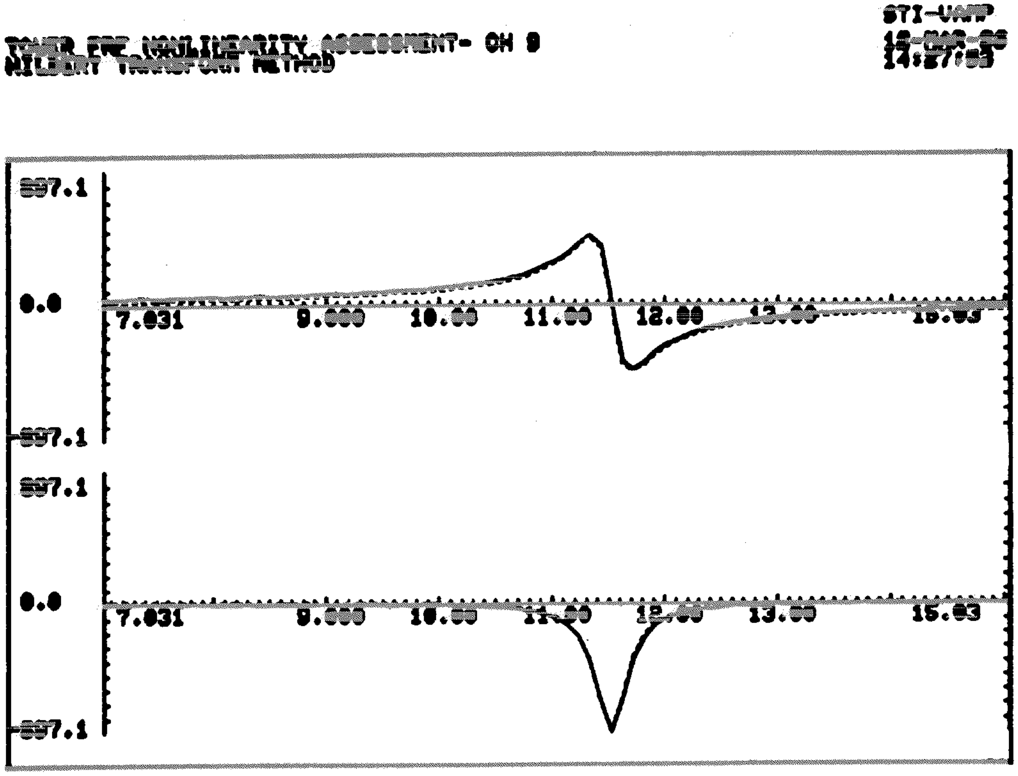
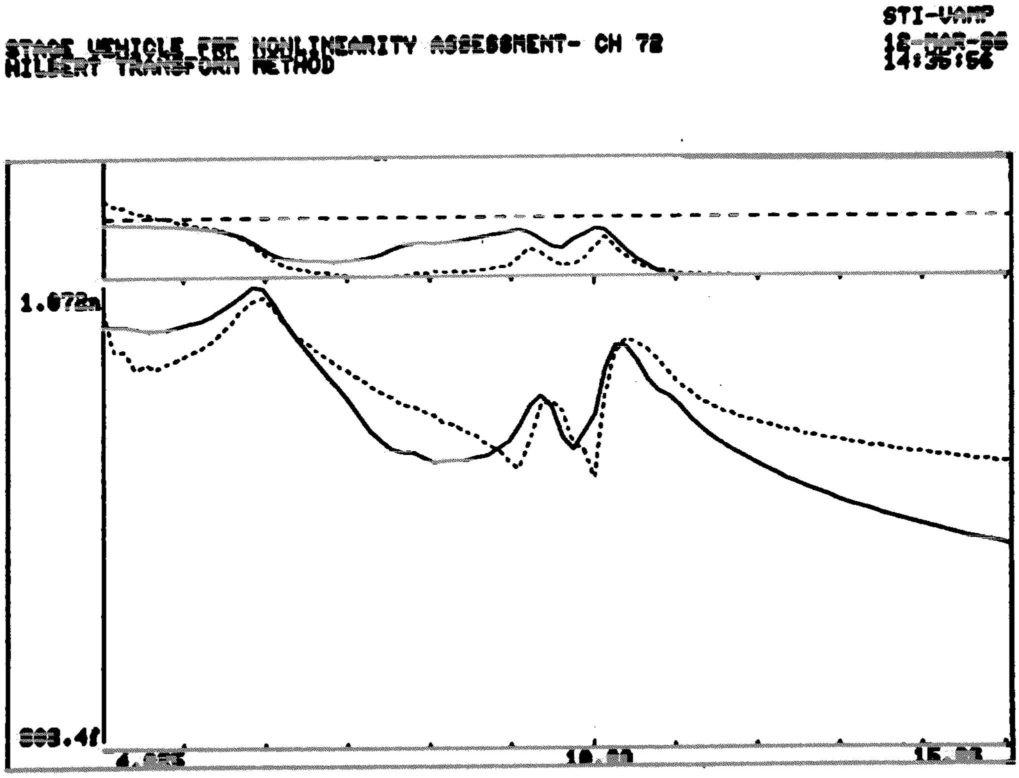


Figure 3a.



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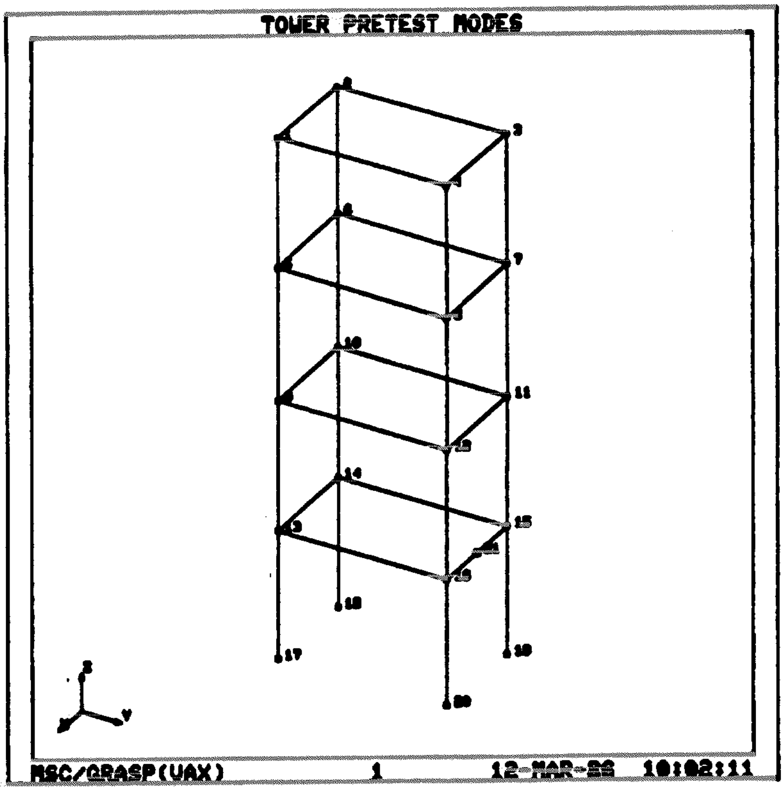

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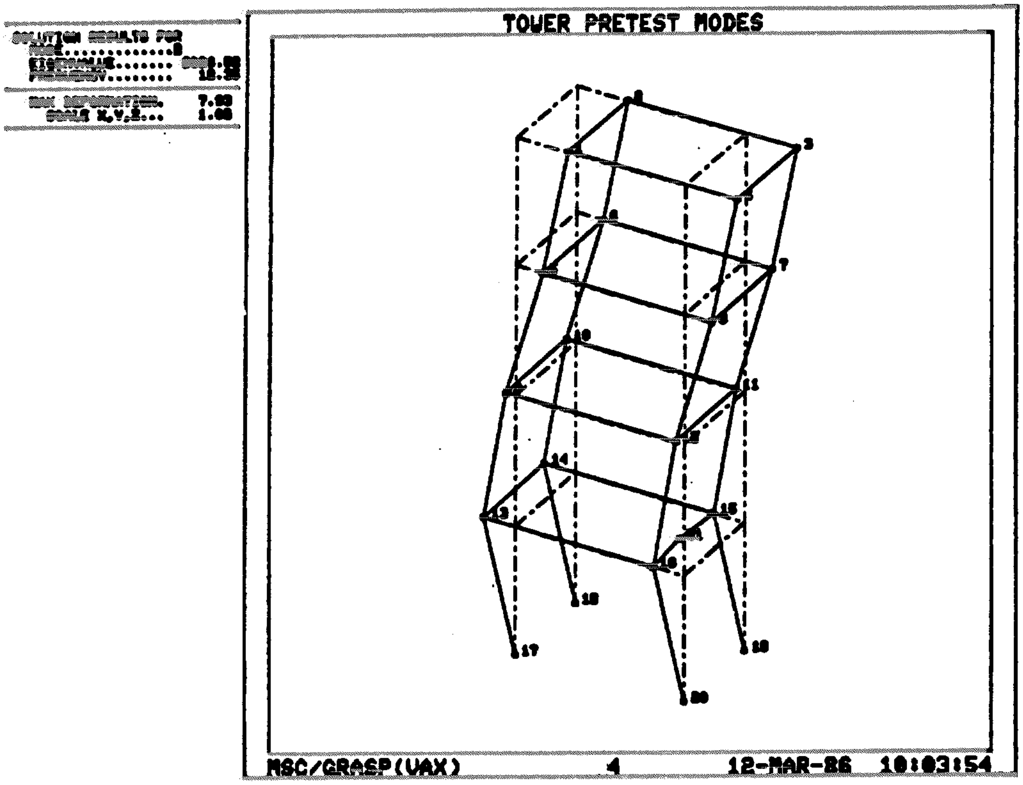

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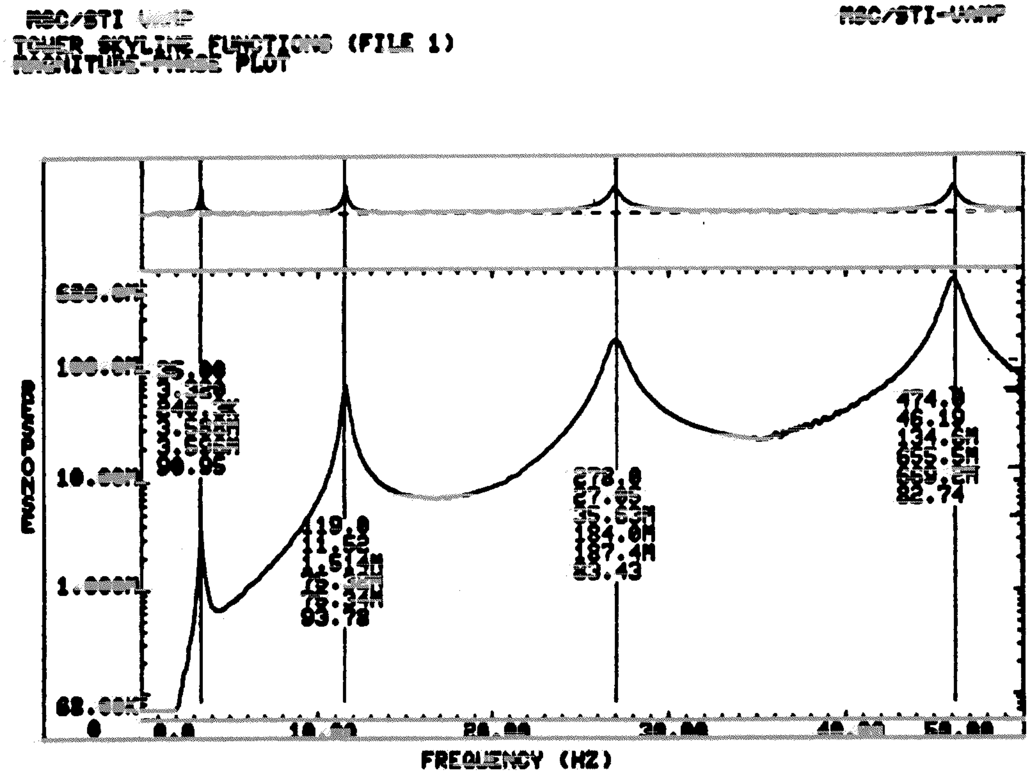

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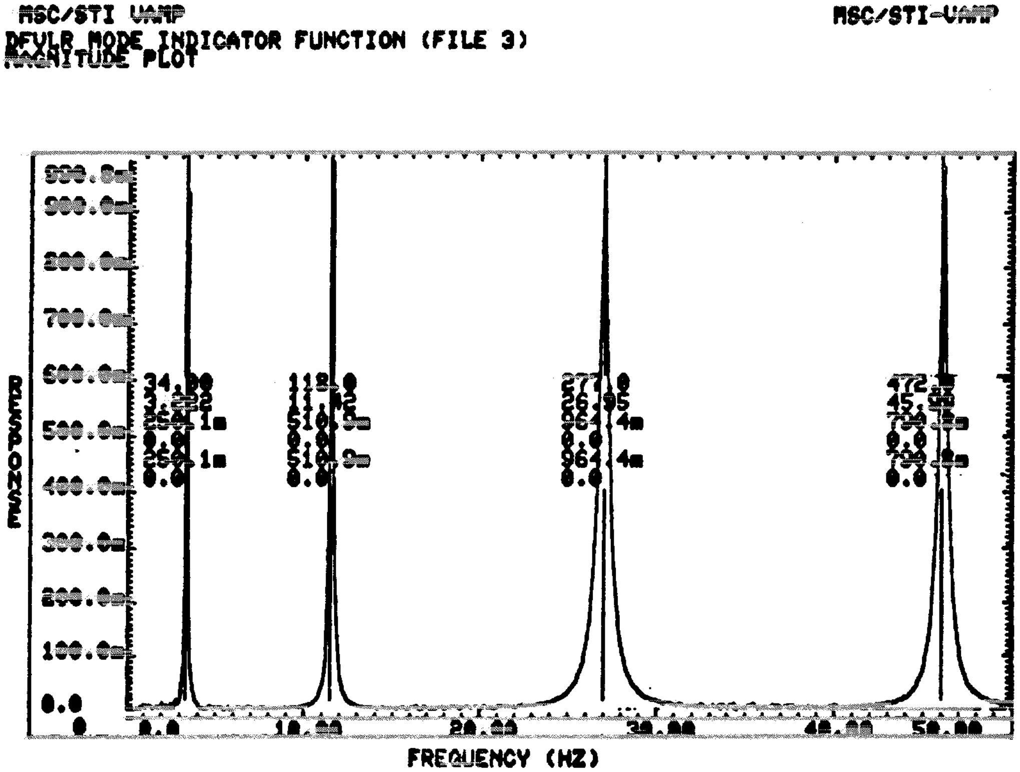

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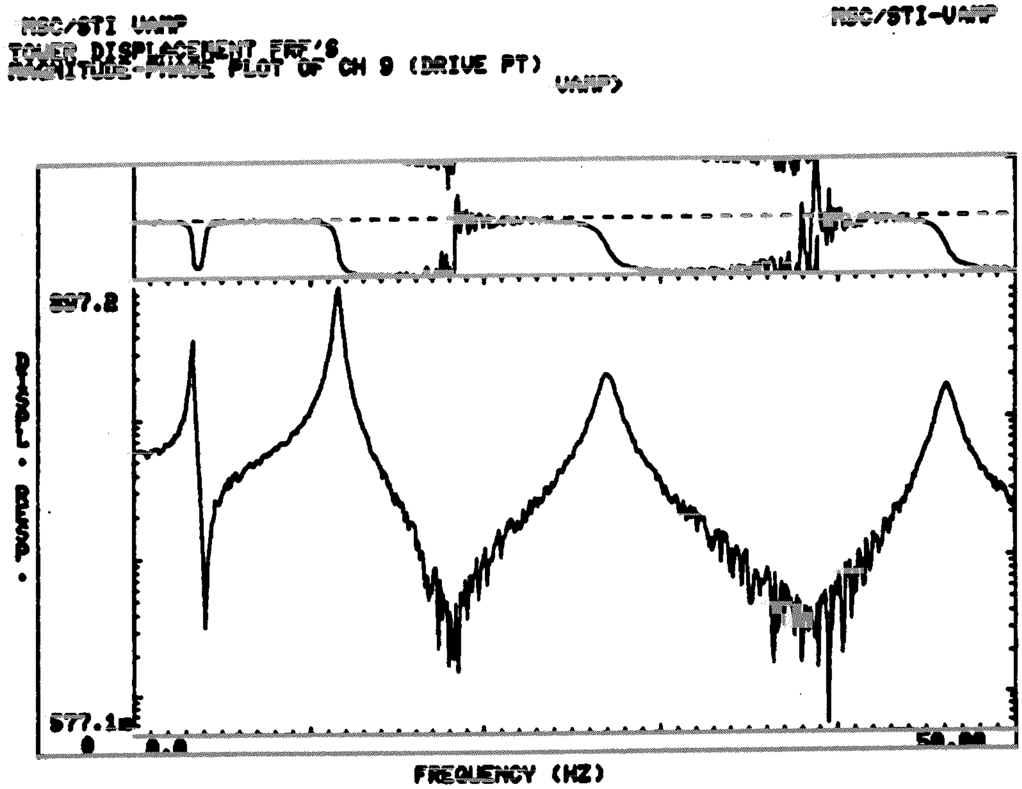
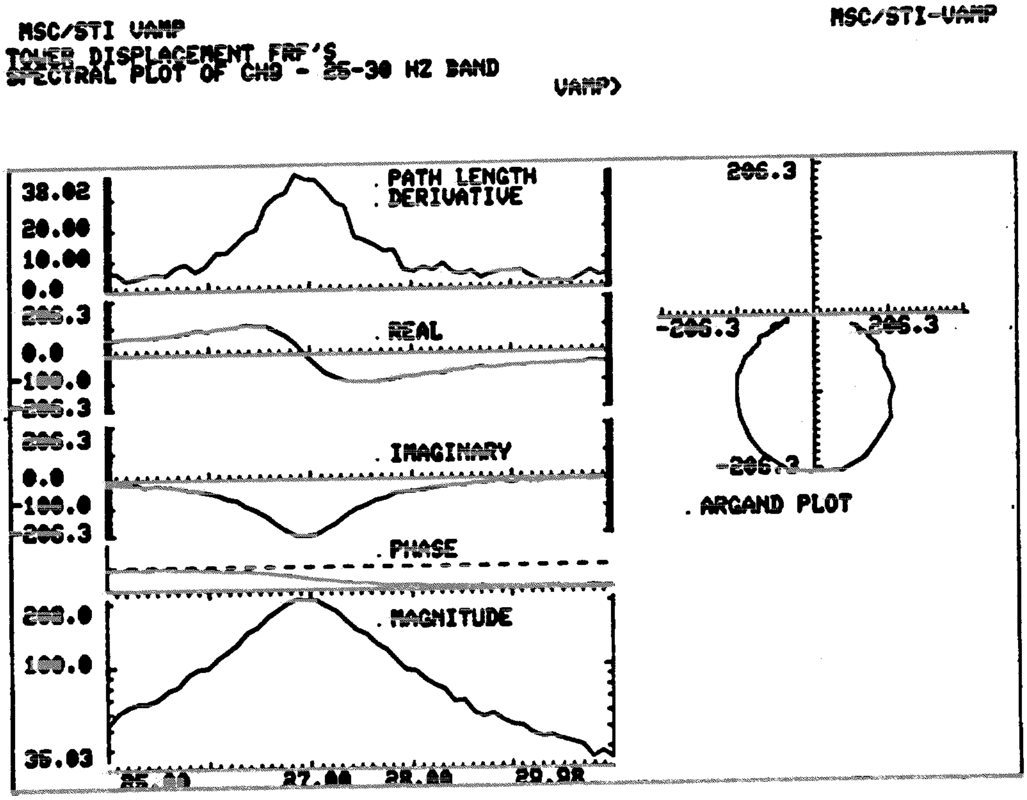


Figure 8.



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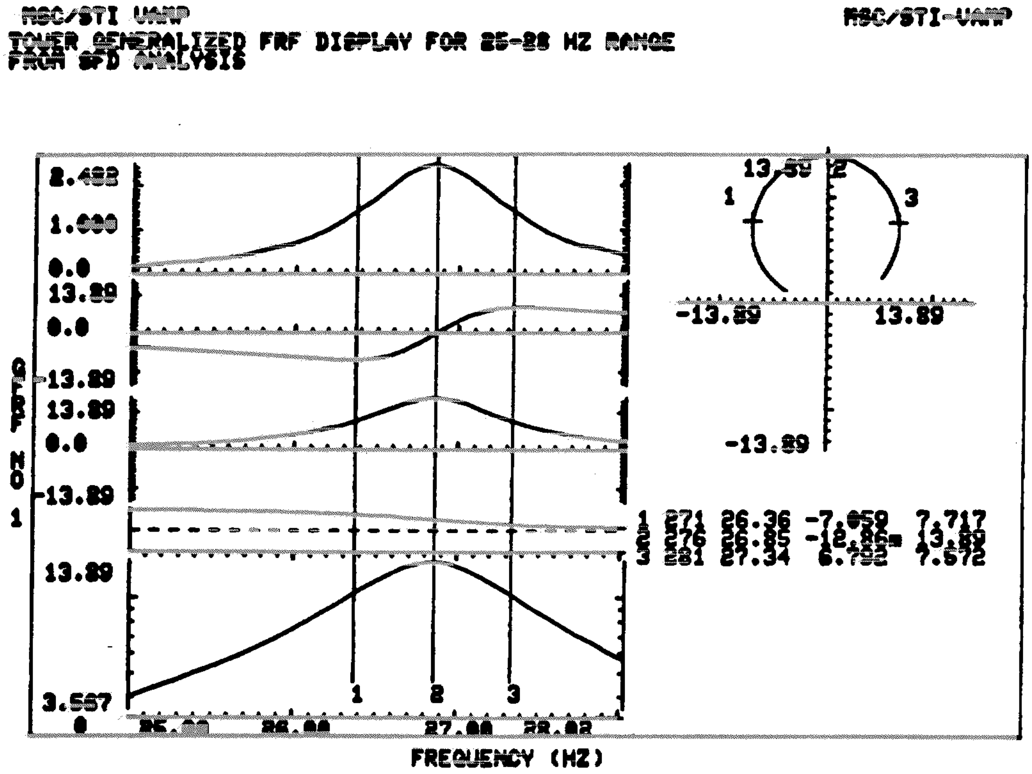

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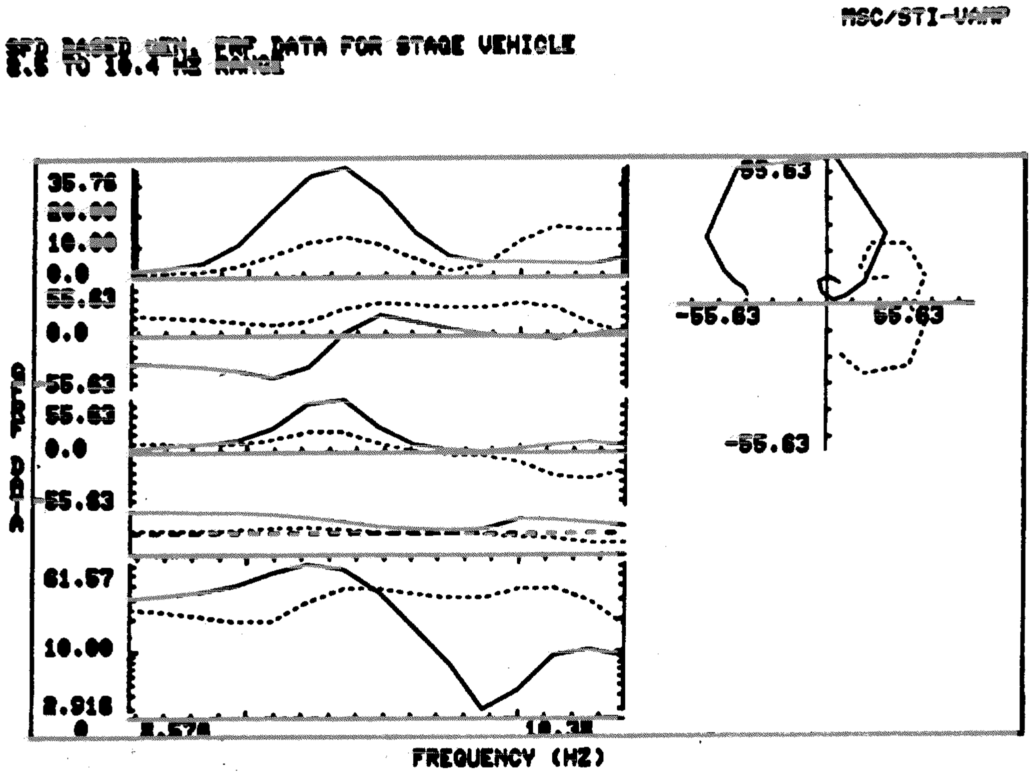

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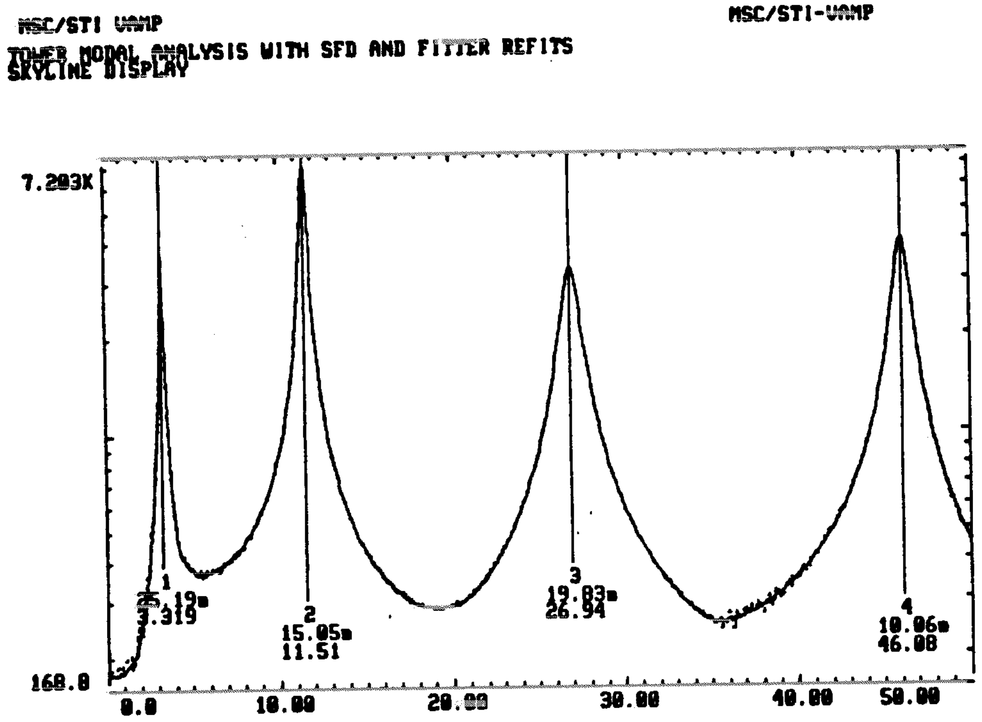

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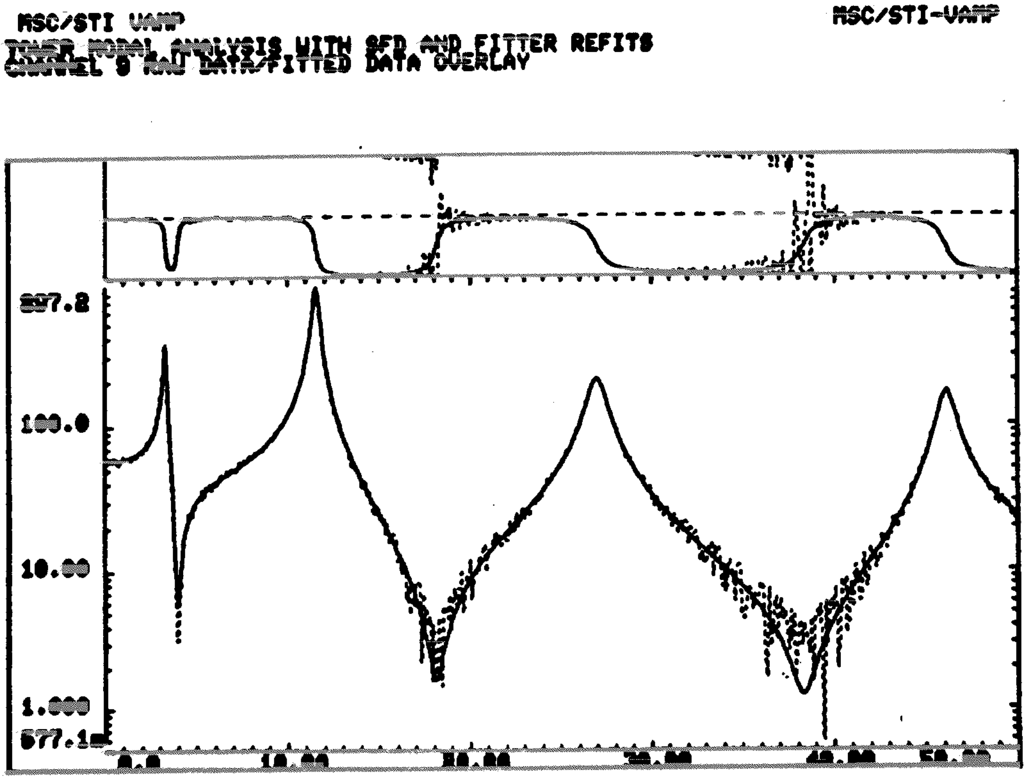
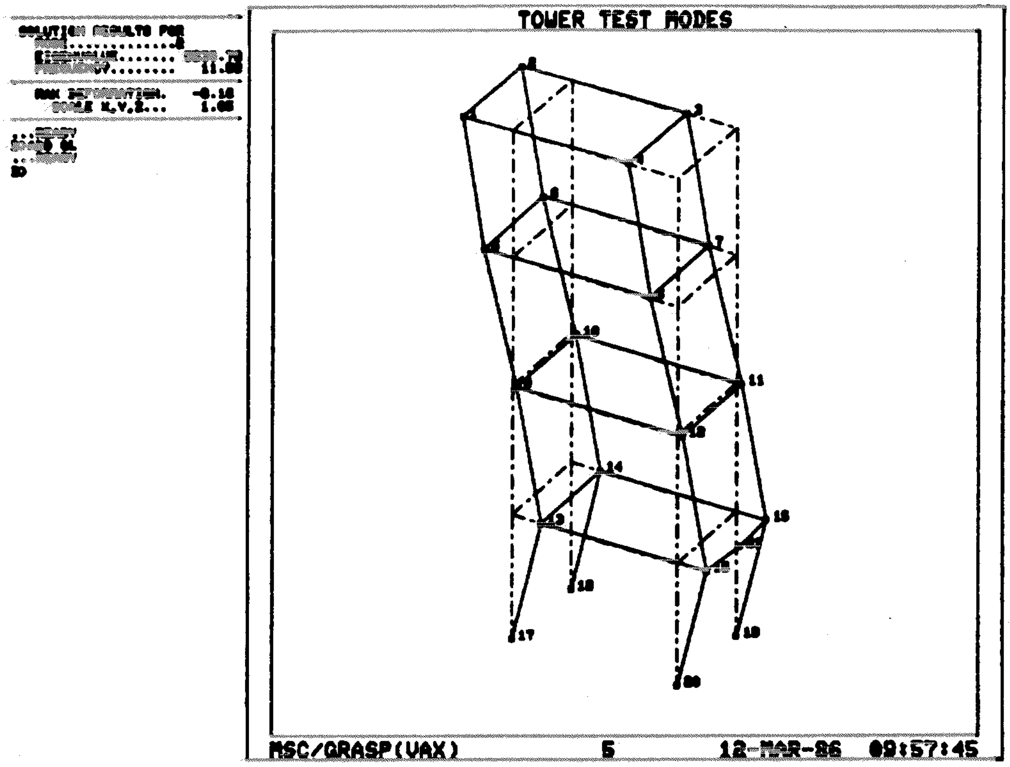


Figure 13.


SOLUTION RESULTS FOR
TOWER TEST MODES
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MSC/GRASP(VAX)
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Figure 14.

TABLE 1

PREDICTED MODAL FREQUENCIES (HZ)
PREDICTED MODES OF TOWER

MODE	A-SET	SUBSPACE	% DIFFERENCE
1	4.005E+00	4.005E+00	3.810E-04
2	1.236E+01	1.235E+01	2.516E-03
3	2.738E+01	2.738E+01	1.912E-02
4	4.616E+01	4.613E+01	6.332E-02

TABLE 2

MODAL EFFECTIVE MASS TABLE

PREDICTED MODES OF TOWER

MODE	1	2	3	4	5	6
1	0.00E+00	3.68E-02	0.00E+00	8.14E+01	0.00E+00	2.81E+00
2	0.00E+00	1.92E-03	0.00E+00	7.44E+00	0.00E+00	1.47E-01
3	0.00E+00	9.75E-05	0.00E+00	1.74E-01	0.00E+00	7.47E-03
4	0.00E+00	4.82E-06	0.00E+00	2.36E-02	0.00E+00	3.69E-04
TOTAL MEFF	0.00E+00	3.88E-02	0.00E+00	8.91E+01	0.00E+00	2.97E+00
TOTAL MASS	4.05E-02	4.05E-02	4.05E-02	1.11E+02	9.43E+01	2.69E+01
% TOTAL MASS	0.00E+00	9.59E-01	0.00E+00	8.04E-01	0.00E+00	1.11E-01

TABLE 3

PREDICTED MODES OF TOWER

MODE NO. 2   FREQUENCY 1.236E+01 HZ

NO.	GRID	DOF	PHI	MOM	ENRG
1	1	2	7.937E+00	2.070E-02	1.643E-01
2	2	2	7.937E+00	2.070E-02	1.643E-01
3	5	2	4.094E+00	1.407E-02	5.761E-02
4	6	2	4.094E+00	1.407E-02	5.761E-02
5	9	2	-1.430E+00	-4.916E-03	7.029E-03
6	10	2	-1.430E+00	-4.916E-03	7.029E-03
7	13	2	-4.823E+00	-1.572E-02	7.582E-02
8	14	2	-4.823E+00	-1.572E-02	7.582E-02
9	21	2	-5.417E+00	-7.208E-02	3.905E-01

TABLE 4

SFD AND REFIT MODE

MODE 2
FREQUENCY = 11.5195
DAMPING = 1.505444E-02
GENERALIZED MASS = 1.00000

CHANNEL	REAL	IMAGINARY	AMPLITUDE	PHASE
1	-591.203	-4.99803	591.224	-179.516
2	-591.203	-4.99803	591.224	-179.516
3	-334.438	-3.19263	334.453	-179.453
4	-334.438	-3.19263	334.453	-179.453
5	51.0391	-0.118074	51.0393	-0.132547
6	51.4444	-0.580291	51.4476	-0.646267
7	340.061	2.24722	340.068	0.378622
8	340.061	2.24722	340.068	0.378622
9	376.145	2.53742	376.153	0.386504

TABLE 5

POST-TEST MODAL EVALUATION

MEASURED MODES OF TOWER

TEST MODAL FREQUENCIES (HZ) AND CRITICAL DAMPING RATIOS

MODE	FREQUENCY	ZETA
1	3.320E+00	2.519E-02
2	1.152E+01	1.505E-02
3	2.694E+01	1.983E-02
4	4.609E+01	1.007E-02

TABLE 6A

ORTHOGONALITY POST-TEST EVALUATION

MEASURED MODES OF TOWER

```
MODE 1

   1 1.00 0.00 0.00 0.00

MODE 2

   1 0.00 1.00 0.00 0.00

MODE 3

   1 0.00 0.00 1.00 0.00

MODE 4

   1 0.00 0.00 0.00 1.00
```

TABLE 6B

CROSS-ORTHOGONALITY POST-TEST EVALUATION

MEASURED MODES OF TOWER WITH RESPECT TO ANALYSIS MODES

```
TEST MODE 1

  1   1.00  -0.07  -0.02   0.00

TEST MODE   2

  1  -0.07  -1.00  -0.03   0.01

TEST MODE   3

  1  -0.01   0.04  -1.00   0.01

TEST MODE   4

  1   0.00   0.01   0.01   1.00
```

TABLE 7

MODAL VECTOR TABLE POST-TEST EVALUATION

MEASURED MODES OF TOWER

MODE NO. 2　　FREQUENCY = 1.152E+01 HZ　　DAMPING = 1.505E+00 %

NO.	GRID	DOF	PHI	MOM	ENRG	DENRA
1	1	2	-8.162E+00	-2.129E-02	1.737E-01	-3.018E-03
2	2	2	-8.162E+00	-2.129E-02	1.737E-01	-2.932E-03
3	5	2	-4.617E+00	-1.587E-02	7.329E-02	5.240E-03
4	6	2	-4.617E+00	-1.587E-02	7.329E-02	4.935E-03
5	9	2	7.046E-01	2.428E-03	1.711E-03	2.528E-02
6	10	2	7.102E-01	2.437E-03	1.731E-03	-1.434E-02
7	13	2	4.695E+00	1.530E-02	7.182E-02	-8.396E-02
8	14	2	4.695E+00	1.530E-02	7.182E-02	-8.367E-02
9	21	2	5.193E+00	6.910E-02	3.588E-01	-3.196E-03

TABLE 8

RECOMMENDED MATHEMATICAL MODEL UPDATES
A-SET ON DIAGONAL STIFFNESS

MEASURED MODES OF TOWER

NO.	GRID	DOF	K-PRE	K-POST	DELTA-K	% K-CHANGE
1	1	2	2.625E+04	2.625E+04	2.155E-02	8.208E-05
2	2	2	2.625E+04	2.625E+04	1.496E-02	5.699E-05
3	5	2	2.633E+04	2.633E+04	2.963E-02	1.125E-04
4	6	2	2.633E+04	2.633E+04	4.351E-02	1.652E-04
5	9	2	2.634E+04	2.635E+04	1.116E+01	4.237E-02
6	10	2	2.634E+04	2.632E+04	-1.503E+01	-5.707E-02
7	13	2	2.647E+04	2.647E+04	-4.241E+00	-1.602E-02
8	14	2	2.647E+04	2.647E+04	-4.197E+00	-1.585E-02
9	21	2	7.282E+02	7.468E+02	1.858E+01	2.552E+00