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Transient Loads Analysis For Space Flight Applications

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ABSTRACT: A significant part of the flight readiness verification process involves transient analysis of the coupled Shuttle-payload system to determine the low frequency transient loads. This paper describes a methodology for transient loads analysis and its implementation for the Spacelab Life Sciences Mission. The analysis is carried out using two major software tools - NASTRAN and an external FORTRAN code called EZTRAN *. This approach is adopted to overcome some of the limitations of NASTRAN's standard transient analysis capabilities. The method uses Data Recovery Matrices (DRM) to improve computational efficiency. The mode acceleration method is fully implemented in the DRM formulation to recover accurate displacements, stresses and forces. The advantages of the method are demonstrated through a numerical example.

1. Introduction: In the past decade, NASA has conducted numerous Spacelab Missions for the advancement of space exploration and research. The Spacelab is a reusable laboratory that is carried in the cargo bay of the Space Shuttle Orbiter. Experiments in several different disciplines such as astronomy, life sciences and material science are accommodated in this modular laboratory for various Shuttle missions. The module also contains utilities, computers and work benches to support the experiments. The experiment hardware is mounted in instrument racks located on either side of the module, in overhead lockers, and in the center aisle, as shown in Figure 1.

During liftoff and landing flight events, the Shuttle and its payload show significant low-frequency transient accelerations due to thrust from the main engines and solid rocket boosters, wind gust, vortex shedding, and launch pad forces during liftoff, and crosswinds and nose-gear slapdown during landing. The levels of acceleration on a specific payload component depend on the response of the Spacelab inside the Orbiter cargo bay and the response of the component inside the Spacelab. Because these responses depend on the dynamic characteristics and interactions of the Orbiter-Spacelab-payload system, a transient analysis of the coupled system is required to determine the quasi-static loads as part of the flight readiness verification process.

Analysis of the coupled system can be carried out using the standard transient analysis capabilities of NASTRAN. However, these procedures have some limitations in terms of computational efficiency and accuracy, especially when dealing with large substructured models [Rf. 1,2]. An alternate procedure which relies on the extensive use of data recovery matrices is presented to overcome some of these limitations. The methodology has been successfully implemented for the analysis of the Spacelab Life Sciences (SLS-2) Mission [Rf.

* EZTRAN is developed by Structural Dynamics Research Corporation, San Diego, California

3] which involved large models (in excess of 190000 degrees of freedom) and long simulations (in excess of 4500 time steps). The advantages of the method are demonstrated through a simple example problem in this paper.

2. Overview of Methods: There are two methods for performing dynamic transient analysis in NASTRAN. The Direct Transient Response, available in Rigid Format 9, solves a system described in terms of its physical mass, stiffness and damping matrices.

$$[m]\{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} = \{f\} \tag{1}$$

These equations are numerically integrated to determine the response at the physical degrees of freedom (DOF) as functions of time. The Modal Transient Response method, available in Rigid Format 12, is similar to the direct method, with the exception that it uses the classical modal transformation

$$\{u\} = [\phi]\{Q\} \tag{2}$$

to diagonalize the physical mass, stiffness and damping matrices. The overall response is calculated by including only a small number of the structural modes, making the numerical integration of the generalized equations of motion much faster.

$$[M]\left\{\ddot{Q}\right\} + [C]\left\{\dot{Q}\right\} + [K]\{Q\} = \{F\} \tag{3}$$

where

$$[M] = [\phi]^T [m] [\phi], \ [C] = [\phi]^T [c] [\phi], \ [K] = [\phi]^T [k] [\phi], \ \{F\} = [\phi]^T \{f\}$$

Physical responses can be recovered from a modal transient analysis through the mode displacement method (Eqn. 2) or the mode acceleration method (Eqn. 4). The former method is more efficient and quite accurate for calculating accelerations if sufficient modes are retained to envelope the frequency content of the forcing functions. However, the latter method is preferred when accurate displacements, element forces and stresses are required from a modal transient analysis. The mode acceleration technique minimizes the loss of accuracy due to modal truncation by including the static response of the truncated high-frequency modes in the solution.

$$\{u\} = [k]^{-1}\left[\{f\} - [m]\{\ddot{u}\} - [c]\{\dot{u}\}\right] \tag{4}$$

The implementation of the mode acceleration procedure in NASTRAN has some disadvantages. In order to include the effects of inertia and damping forces in the load vector in Eqn. 4, the accelerations and velocities at all DOF in the solution set (L-set) must be computed. A static solution must then be performed with the modified load vector at each time step. This requires significant computer processing time if the L-set is large and/or the number of integration steps is large. In addition, there are accuracy problems when dealing with multi-stage substructured models. For such cases, the mode-acceleration correction is applied only to the residual structure and not to upstream substructures. This leads to modal truncation errors because the component modes are used to represent the static response of the interior degrees of freedom [Rf. 1].

Because of these disadvantages, standard transient analysis procedures in NASTRAN are not suitable for solving large problems involving multi-stage substructured models. Alternate methods are required to overcome these limitations, and yet retain the benefits of the mode acceleration method. Such a procedure, used for transient loads analysis of the SLS-2 Mission configuration, is described in the following section.

3. Alternate Method: The alternate method is based on a slightly different form of the mode acceleration data recovery equation. Assuming that damping is negligible, Eqn. 4 can be expressed in the following convenient form.

$$\{u\} = [\psi]\{p\} - [\phi]\left[\Lambda^{-1}\right]\left\{\ddot{Q}\right\} \tag{5}$$

The first term represents the static portion of the transient response. It is obtained as the product of ψ, the static response caused by a set of *unit loads*, I, and a time varying load scale factor, $p(t)$. Note that the *unit loads* multiplied by the scale factor are equivalent to the applied loads, i.e.,

$$\{f(t)\} = [I]\{p(t)\} \tag{6}$$

The second term in Eqn. 5 represents the dynamic portion of the response. It usually includes only the elastic mode contributions as the rigid body modes (if any) do not contribute to stresses and forces. However, the contribution from rigid body modes to the total displacement, $[\phi_{rb}]\{Q_{rb}\}$, can be included in Eqn. 5 if desired. The computational advantages of the alternate method stem from the size of the $[\psi]$ and $[\phi]$ matrices which are determined by the number of response recovery points, the number of load application points and the number of retained elastic modes. These are usually much smaller than the full model size.

The alternate method is implemented using two major software tools - NASTRAN and an external FORTRAN program called EZTRAN. NASTRAN is used to develop, process and assemble the finite element model of the coupled system, calculate system modes, determine unit load static responses, and create data recovery matrices. EZTRAN calculates the modal initial conditions, solves the generalized equations of motion, and recovers physical results. The following steps describe how the two work in conjunction to perform the various analysis tasks.

3.1 Model Generation and Assembly: Finite element models of the Orbiter, Spacelab and experiment payloads are developed by different organizations and are usually test-verified models. They are assembled into a solution system using the automated multi-stage substructuring features of NASTRAN. Prior to assembly, the quality of each component model is verified by performing a series of analytical checks including rigid body modes check, stiffness matrix equilibrium check, rigid body mass check and an enforced displacement check. At each stage of assembly, the effective DOF in the model is reduced either through a Guyan reduction (REDUCE) or a modal reduction (MREDUCE). A fixed-interface Craig-Bampton modal reduction is the preferred method as it will not compromise the fidelity of test-verified finite element models.

3.2 Loads Definition: The input forcing functions for coupled loads analysis are obtained from previous flight accelerometer data. These are maintained by NASA and provided to payload organizations during design evaluation to refine design loads. The data is provided in terms of discrete force-time coordinate pairs, with the point of application of each force being identified by a node number and component name. They include multiple load cases for liftoff and landing flight events. Load scale factors are generated for each load case by normalizing the system forcing functions with unit loads, as indicated in Eqn. 6. The ***unit loads*** are defined as the maximum force occuring at each loaded DOF, across all load cases.

3.3 Normal Modes Analysis: A normal modes analysis of the fully assembled system is performed using NASTRAN Rigid Format 3. The rigid body modes and the elastic modes of the system, in a specified frequency range, are recovered and stored in the substructure operating file (SOF) database. The frequency range for modal truncation is decided based on the frequency content of the excitation.

3.4 Unit Load Static Analysis: An inertia relief static analysis is performed on the fully assembled system for unit loads derived from the liftoff and landing forcing functions. An unit load vector is generated for each loaded DOF, and they are sequenced in the same order as the forcing functions to form a unit load matrix. The static analysis is performed using Rigid Format 2 because it is capable of analyzing structures with rigid body modes. SUPORT cards must be included if rigid body modes are present, and the choice of support points has significant effect on the computation of displacement results. A good choice is indicated by low strain energy at the support points. An unreduced model is used for static analysis in order that the full mass matrix be available for calculating internal inertia loads of upstream substructures. The static displacements from the inertia relief solution are recovered and stored in the SOF database.

3.5 Data Recovery Matrices Generation: The alternate procedure requires the generation of acceleration and displacement data recovery matrices. These are formed for each basic substructure by performing two data recovery (Phase 3) restart runs with special DMAP alters. The acceleration DRM is made up of rigid body modes and retained elastic mode vectors. These are extracted from the normal modes database for DOF specified through XYPLOT/XYPEAK requests in the SOL 3 data recovery run.

$$\text{Acceleration DRM} = [\phi_{rb} \quad \phi_{el}] \tag{7}$$

Displacements and displacement dependent responses such as element forces, stresses and substructure interface loads are recovered using the mode acceleration method. The displacement DRM has two partitions. The first consists of the unit load static deflection vectors which are extracted from the static analysis database. The second, which provides the dynamic contribution, is obtained from the normal modes database. A rigid format alter in the SOL 2 data recovery run assembles the full displacement DRM for responses specified through XYPLOT/XYPEAK requests.

$$\text{Displacement DRM} = \left[\psi \quad \phi_{el}\Lambda_{el}^{-1}\right] \tag{8}$$

The size of the DRMs is controlled by many factors. The number of rows in the acceleration and displacement DRMs will correspond to the number of response requests in the data recovery runs. Since the number of output requests is usually much smaller than the model size, data recovery operations using DRM procedures are much faster than standard methods. The number of columns in the acceleration DRM will correspond to the number of retained system modes. The number of columns of the displacement DRM will be equal to the sum of the retained elastic modes and the number of load application points.

3.6 EZTRAN Execution: The solution of the generalized equations of motion and the recovery of physical responses are accomplished by EZTRAN using the NASTRAN generated data. The information provided to EZTRAN is shown in Figure 2. The generalized mass and stiffness matrices and the generalized unit forces, $F_u = \phi^T I$, are supplied by NASTRAN through a model file. The scaled forcing functions are supplied through a forcing function file. Specific instructions for an EZTRAN run including load cases to be analyzed, time step information, number of modes to be included, modal damping parameters, and type of initial conditions are entered by the user in an input file. The NASTRAN generated DRMs are supplied through a matrix file. A dictionary file provides identification for the response items in the DRMs.

The modal equations of motion are uncoupled by virtue of linearity and proportional damping assumptions.

$$[M]\left\{\ddot{Q}\right\} + [C]\left\{\dot{Q}\right\} + [K]\{Q\} = \{F_u\}\{p(t)\} \tag{9}$$

They are solved using a simple recursive algorithm [Rf. 4]. The solution is exact within the limits that the applied forces are assumed to vary linearly between integration steps. The method is unconditionally stable, regardless of integration step size. However, the step size must be sufficiently small so that linear interpolation accurately follows the applied force time histories. Initial conditions are either zero (undeformed structure) or can be automatically computed by EZTRAN, assuming that the system is in steady-state equilibrium with initial non-zero forces. For example, the Orbiter and payloads are initially deflected by gravity, wind loads, and restraining forces at the launch pad attach bolts, and are in steady state equilibrium. The deflections of elastic modes and acceleration of rigid body modes are computed from the initial modal forces by EZTRAN for such cases.

The solution of modal differential equations yields the modal acceleration, $\ddot{Q}$. Physical responses are recovered using these solutions and the DRMs.

$$\left\{\begin{matrix}\text{Physical}\\ \text{Accelerations}\end{matrix}\right\} = \left[\begin{matrix}\text{Acceleration}\\ \text{DRM}\end{matrix}\right]\left\{\ddot{Q}(t)\right\} \tag{10}$$

$$\left\{ \begin{array}{c} \text{Physical Displacements and} \\ \text{Displacement dependent} \\ \text{Responses} \end{array} \right\} = \left[\begin{array}{c} \text{Displacement} \\ \text{DRM} \end{array} \right] \left\{ \begin{array}{c} p(t) \\ \ddot{Q}(t) \end{array} \right\} \tag{11}$$

3.7 Post Processing: The results from EZTRAN include minimum/maximum summaries and time histories for the response items selected in the data recovery runs. The responses can be scaled by static and dynamic uncertainity factors to account for possible variations in the dynamic models or forcing functions. The results are written to formatted files that can be read by other postprocessing programs to provide extrema reports, response history plots, shock response spectra, relative displacements, and other output.

4. Example Problem: To illustrate the accuracy and efficiency of the alternate method, an example problem was analyzed. The problem consists of simple models of the Orbiter, Spacelab, Floor, Rack and a Box which were assembled into a solution system as shown in Figure 3. Modal reductions were performed at each stage of substructure assembly. The model was analyzed for a dynamic transient load case which had 45 load application points on the Orbiter substructure.

The analysis was performed using three different approaches. The first analysis used the direct transient solution feature of NASTRAN to solve a full, unreduced model of the system (3971 DOF). Although this approach is not practical for most real world problems, it provides an accurate baseline solution without any modal truncation errors. The second analysis used the modal reduced system model (205 DOF) with modes up to 35 Hz being retained in the final solution system. The transient analysis was performed in the modal domain, and the physical responses were recovered using NASTRAN's mode acceleration method. Finally, the transient analysis was performed on the same modal reduced system model using the alternate mode acceleration method. All three cases were undamped with zero initial conditions. The simulations were carried out for 0.5 seconds with an integration time step of 0.001 seconds.

A comparison of the cost and accuracy of the three methods clearly demonstrates the merits of the alternate method. The axial forces in a CBAR element of the BOX substructure are shown in Figure 4. The alternate method produces results which are much closer to the baseline solution than the NASTRAN mode acceleration solution. Similar results were obtained for other displacement dependent responses. In addition to being accurate, the alternate method was also more efficient than the other methods, as shown in Figure 5. The computational advantages of the alternate method become more pronounced as the length of simulation increases.

5. Conclusions: An accurate and efficient method for performing coupled transient loads analysis was presented and compared with the standard transient analysis capabilities of NASTRAN. The procedure uses data recovery matrices to reduce matrix size and computation times. The mode acceleration method is incorporated in the DRM formulations to recover accurate displacements and displacement-dependent quantities like element stresses, element forces and interface loads. The method is ideally suited for large, multi-level substructured models.

6. References:

1. Chris C. Flanigan. Accurate and effiecient mode acceleration data recovery for superelement models. 1988 MSC/NASTRAN World Users Conference.

2. Chris C. Flanigan. Effiecient and accurate procedures for calcuting displacement data recovery matrices. 1989 MSC/NASTRAN World Users Conference.

3. Spacelab Life Sciences 2 (SLS-2) Design Coupled Loads Analysis Report. *JSC-25200* 1991

4. EZTRAN User's Manual. Structural Dynamics Research Corporation. 1991.

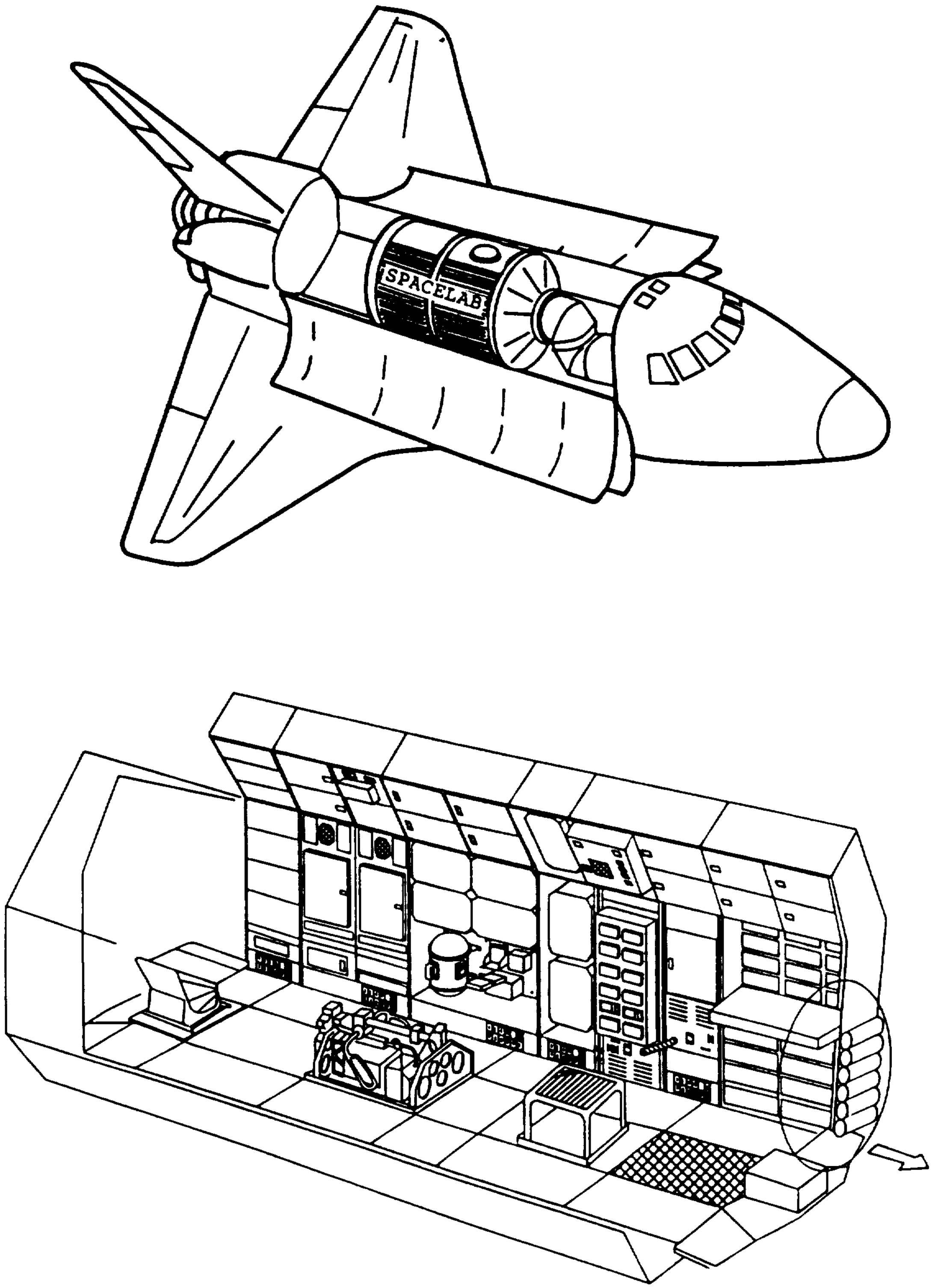


FIG. 1. TYPICAL SPACELAB CONFIGURATION

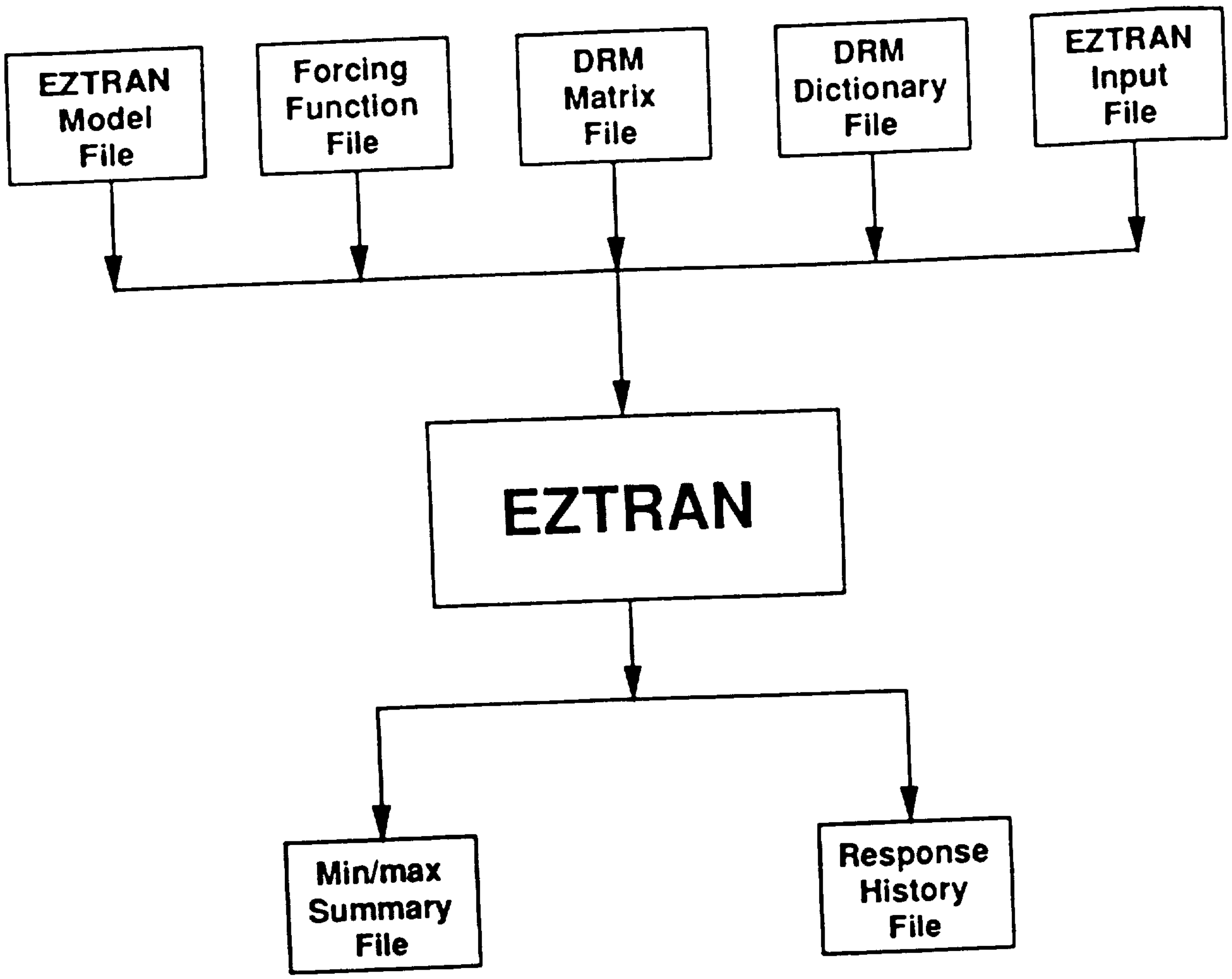


FIG. 2. EZTRAN INPUT AND OUTPUT FILES

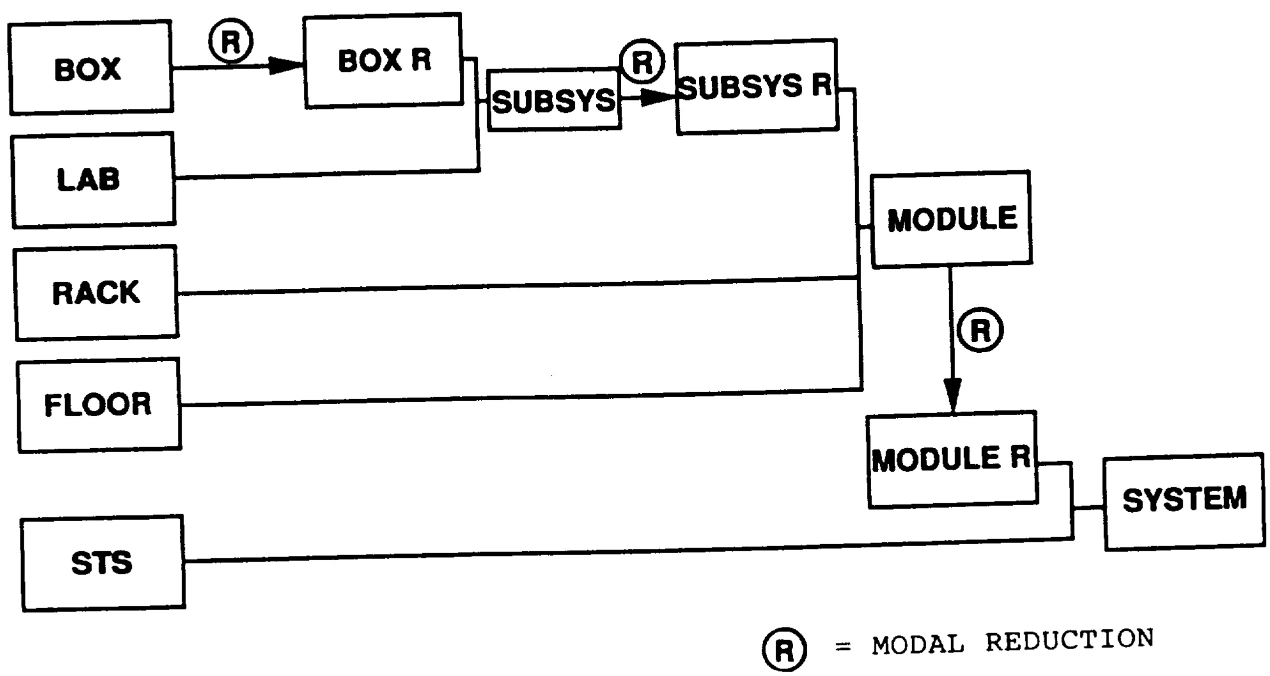
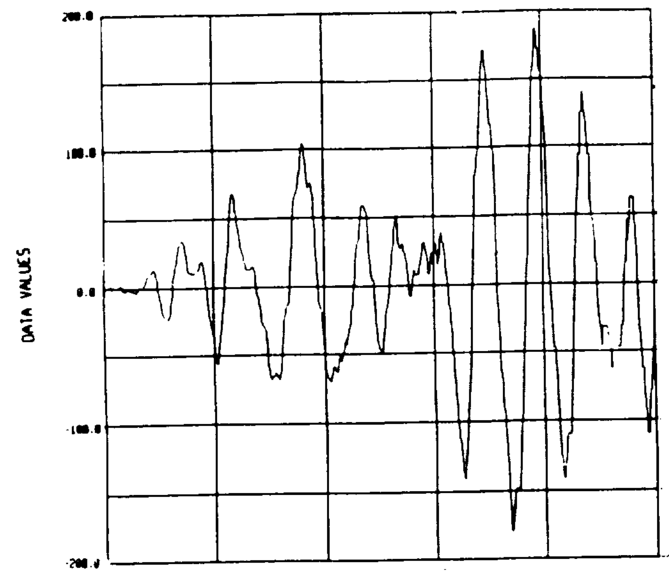
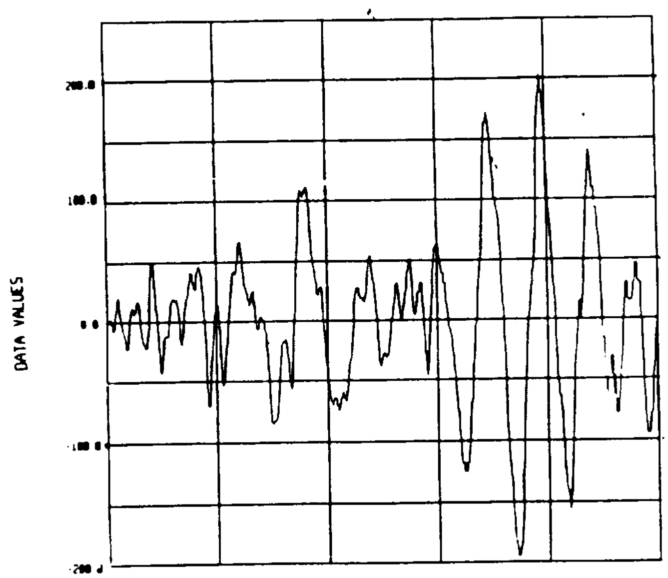


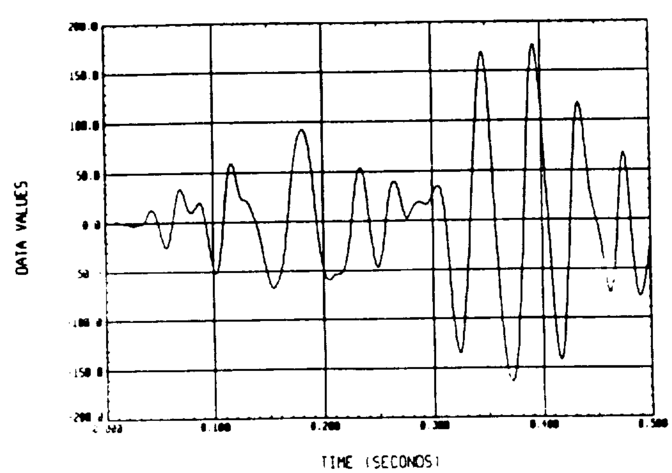
FIG. 3. THE SOLUTION SYSTEM ASSEMBLY SCHEME



a) DIRECT METHOD
FULL UNREDUCED MODEL

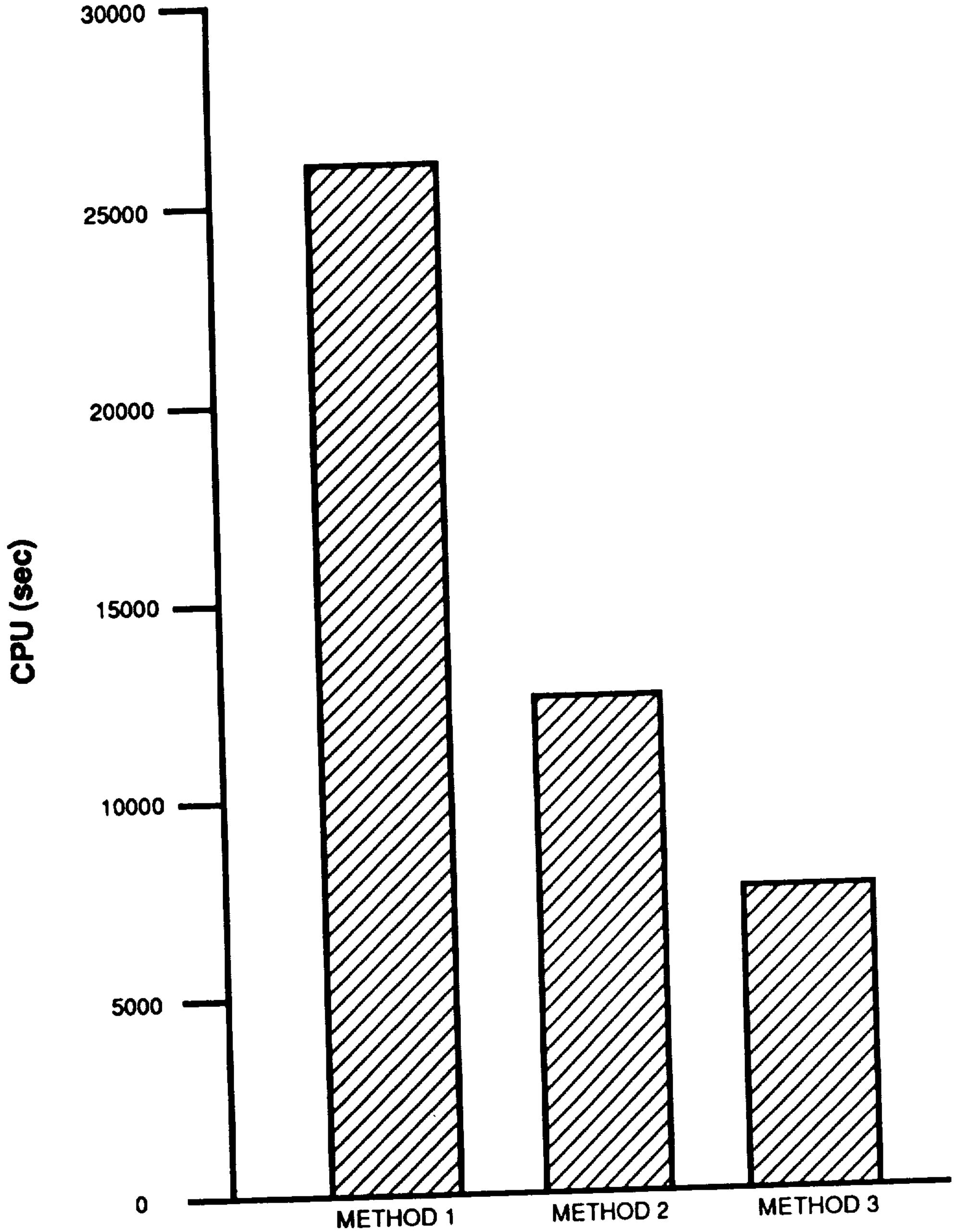


b) NASTRAN MODE
ACCELERATION METHOD



c) ALTERNATE MODE
ACCELERATION METHOD

FIG. 4. AXIAL FORCE IN CBAR 2031, BOX SUBSTRUCTURE



METHOD 1 - NASTRAN Direct Solution of Full Unreduced Model

METHOD 2 - NASTRAN Mode Acceleration Method

METHOD 3 - Alternate Method

FIG. 5. RELATIVE EFFICIENCY OF TRANSIENT ANALYSIS METHODS