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Solving Modal Equations of Motion with Initial Conditions Using MSC/NASTRAN DMAP Part 2: Coupled vs. Uncoupled Integration

Alan R. Barnett, Omar M. Ibrahim, and Ayman A. Abdallah
Analex Corporation
Brook Park, Ohio

and

Timothy L. Sullivan
Lewis Research Center
Cleveland, Ohio

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Part 2: Coupled vs. Uncoupled Integration

Alan R. Barnett, Omar M. Ibrahim, and Ayman A. Abdallah
Analex Corporation
3001 Aerospace Parkway
Brook Park, Ohio 44142

Timothy L. Sullivan
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

By utilizing MSC/NASTRAN DMAP in an existing NASA Lewis Research Center coupled loads methodology, solving modal equations of motion with initial conditions is possible using either coupled (Newmark-Beta) or uncoupled (exact mode superposition) integration available within module TRD1. Both the coupled and newly developed exact mode superposition methods have been used to perform transient analyses of various space systems. However, experience has shown that in most cases, significant time savings are realized when the equations of motion are integrated using the uncoupled solver instead of the coupled solver. Through the results of a real-world engineering analysis, advantages of using the exact mode superposition methodology are illustrated.

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Nomenclature

Abbreviations

DOF   Degrees-of-freedom
DMAP   Direct Matrix Abstraction Program
IEA   Integrated Equipment Assembly
LeRC   Lewis Research Center
NASA   National Aeronautics and Space Administration
STS   Space Transportation System (Space Shuttle)
WP-02   Space Station *Freedom* Work Package 2
WP-04   Space Station *Freedom* Work Package 4

Introduction

As presented in [1], a solution algorithm was developed using MSC/NASTRAN DMAP whereby linear system modal equations of motion with initial conditions can be solved utilizing the uncoupled integration routine [2] within DMAP module TRD1. It was shown that the total modal response due to the loads acting on the system can be solved for as the superposition of two responses. The first response is a shifted transient solution due to loads equal to the original applied loads minus the loads at time t = 0.0. The second response is a steady-state solution caused by the constant initial loads acting on the system. The implementation of the exact mode superposition methodology was an enhancement to the NASA Lewis Research Center coupled loads methodology [3]. Using a simple numerical example [1], it was shown that the new exact mode superposition method is very accurate for solving system modal equations of motion with initial conditions.

Solving system modal equations of motion with initial conditions has been possible with the NASA LeRC coupled loads methodology. The only limitation was that the analyst was forced to use coupled integration (modified Newmark-Beta [4]) solver due to the logic within DMAP module TRD1. In order to use the more efficient and reliable uncoupled solver within TRD1, the exact mode superposition method was developed and implemented.

Another motivation for developing the exact mode superposition methodology concerned time step selection. The process for selecting integration time steps for solving modal equations of motion can be lengthy. The analyst must take into consideration the definition and frequency content of the input loads, the expected frequency of output

responses, and the overall analysis cost. If too large a time step is chosen, the representation of the input load, and hence, modal solution will be inaccurate. Conversely, if too fine a time step is chosen, computational costs can be prohibitive. When using a Newmark-Beta integration routine, additional time must be spent to insure the algorithm has converged to the accurate modal solution. Eventually the Newmark-Beta algorithm will converge to the exact modal solution given a fine enough integration time step, but the resulting analysis time (and cost) may be large. Hence, an accurate modal solution with a reasonable analysis cost not requiring a lengthy procedure for selecting integration time steps was needed.

The exact mode superposition methodology was developed and implemented based on what was noted during a STS transient liftoff analysis. The analysis was performed with the coupled solution algorithm, and a considerable effort was spent selecting the very small integration time step required to converge to a system modal solution. Hence, the analysis was inefficient and costly. After the exact mode superposition methodology using uncoupled integration was implemented, a reanalysis of the STS liftoff was performed. By comparing the results and resource requirements of both analyses, the advantages realized using the new method could be assessed via a real-world engineering problem.

As was alluded to earlier, a motivation for developing the exact mode superposition method was the need for an efficient method not requiring a lengthy integration time step selection process. Procedures for selecting integration (and output) time steps when considering coupled and uncoupled integrators are outlined in the next section. Following that, the STS liftoff analyses performed using the coupled and exact mode superposition methods is described. Results from the analyses are compared in a subsequent section. Lastly, conclusions will be drawn concerning coupled versus uncoupled integration for modal equations of motion with initial conditions.

Time Steps

Accurately solving for system modal responses due to transient loads is dependent upon the time step of integration. In many cases when analyzing aerospace systems forced by severe transients, very fine time steps are required to accurately integrate the equations of motion and recover peak physical responses. Unfortunately, finer time steps translate into longer analysis times, and costs can become prohibitive.

When solving modal equations of motion, the process followed to select integration time steps can be lengthy depending upon whether the solution routine employs coupled or uncoupled integration. To aid in selecting the optimum integration time step for a particular transient analysis, the procedure outlined in Fig. 1 can be followed. The procedure takes into account both the coupled (Newmark-Beta) and uncoupled (exact mode superposition) solution methodologies. Note that the procedure involves recovering selected physical responses. These items constitute a very small subset of the total amount of responses finally recovered. Output time steps for data recovery are chosen as multiples of the integration time steps. It is important to note that engineering judgement plays a big part in defining how frequent data recovery is output in order to capture peak responses.

The first step in the procedure is the selection of an initial integration time step (t_i in Fig. 1). This is done using two candidate time steps. The first candidate time step (t_1 in Fig. 1) is derived from the input transient loads. It is assumed the transient loads are well defined. The best approximation of the loads occurs when integration is performed at every time instant loads are specified. A FORTRAN code was developed which processes the MSC/NASTRAN bulk data load definition cards and determines times at which loads are defined. These data are used to choose t_1. Hence, t_1 insures a best representation of the input transient loads for both integration routines.

While t_1 insures a best approximation of the input transient loads, it does not insure that peak output responses will be captured by both methods. Hence, a second time step is derived. The second candidate time step (t_2 in Fig. 1) is calculated using an accepted "rule-of-thumb" for capturing peak responses of output for both the coupled and exact mode superposition methods. Time step t_2 is calculated as one over ten times (or more) the highest system modal frequency.

Given the candidate time steps t_1 and t_2, they are compared. If t_1 is less than or equal to t_2, it is assured that the input load time histories are best approximated, and there is a very good chance that peak responses will be captured.

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Hence, t_1 is chosen as the initial integration time step t_i for both methods. If t_1 is greater than t_2, the best approximation of the transient loads is still assured, but peak responses may not be recovered. Hence, integral fractions of t_1 are calculated until t_1 is less than or equal to t_2. This subdividing guarantees that integration still occurs at all time instants transient loads are defined. The final t_1 value is then chosen as the initial integration time step t_i for both methods.

After the initial integration time step is chosen, the modal responses are solved for, and selected physical responses are recovered using both methods. Accurate integration is guaranteed when uncoupled integration is performed; and hence, it is only done once. An accurate integration is not insured for the coupled integration because it is an approximate numerical method. Although the Newmark-Beta method is unconditionally stable for a given time step, it can converge to an inaccurate result depending on the time step size [5]. To insure accurate results, an iterative approach must be taken whereby the analysis is performed using finer and finer integration time steps until a converged solution results. Responses are recovered for a small subset of data recovery items, and once converged responses are obtained, the final time step for the coupled method (t_f in Fig. 1) is defined. Given the results and resource requirements of both methods, the more efficient method and corresponding integration time step are chosen. After this, the full analysis is performed whereby all required physical responses are recovered.

STS Liftoff Analyses

To compare the performances of the coupled and the exact mode superposition methods, STS liftoff transient analyses were performed. The payload analyzed was the first cargo element to be launched for Space Station *Freedom*. It is known as the WP-02/WP-04 Combined Cargo Element, and a schematic of the design is shown in Fig. 2. Modal responses were solved for using both the Newmark-Beta and exact mode superposition algorithms. Selected physical responses were then recovered using all modal solutions. The physical responses were compared, as were CPU times required for analysis.

The payload finite element model is shown in Fig. 3. The model weight is 30,343 lb., and it consists of 4470 elements and 16,956 MSC/NASTRAN g-set DOF. To reduce the size of the physical payload model, the model was dynamically reduced to eight physical interface DOF and its 222 fixed-interface component modes from 0.0 to 75.0 Hz. The STS liftoff model consists of 96 physical interface DOF and 610 fixed-interface component modes from 0.0 to 70.0 Hz. It weighs 4,465,162 lb.

Using MSC/NASTRAN superelement capabilities, component mode synthesis [6] was used to couple the payload model to the STS model. The superelement tree is shown in Fig. 4. The eight payload physical interface DOF were coupled to eight STS physical interface DOF, and an eigensolution was performed on the free-free coupled system. Six rigid-body modes and 576 elastic modes were calculated up to 50.0 Hz. Proportional damping was applied at the system modal level. No damping was applied to the rigid-body modes, 1% critical damping was applied to all elastic modes up to 10.0 Hz., and 2% critical damping was applied to all elastic modes above 10.0 Hz.

For a typical STS liftoff analysis, eleven transient load cases are analyzed. Many loads representing winds, STS main engine build-up and hold, and STS solid rocket booster ignition are applied to the system. The liftoff analyses for method comparisons were performed over an eleven second time interval for a single liftoff load case. For all analyses, the integration time step was selected based on the criteria described in the preceding section. The time steps between transient load definitions were smaller than a time step calculated using the "rule-of-thumb," and the integration step was set as 0.001 sec. When the exact mode superposition method was used, the analysis was performed only once. When the coupled integration method was used, three analyses were performed in order to check for convergence. Each subsequent analysis used an integration step size equal to one half the previous step size. In terms of requesting output, experience has shown that for STS liftoff analyses, peak physical responses occur between six and ten seconds during the analysis. Hence, output time requests were specially tailored. Integration and output time step sizes used for all analyses are listed in Table 1.

Selected physical data recovery was performed using the mode acceleration method [3] for the payload model in all analyses. The thirteen selected items represent interface loads between various payload components. Referring to

Table 1, it should be noted that the frequency of data recovery output was a function of the integration time step definition. Output timing for recovering physical responses was the same for all analyses.

Discussion of Results

The reason for performing the STS liftoff analyses was to compare the performances of the exact mode superposition and coupled solution methods. The objective was to efficiently obtain accurate physical responses. Thirteen interface loads were considered in the comparisons. Interface loads were chosen since their values are a function of both acceleration and displacement data. The ratios of the absolute maximum responses and corresponding times of occurrence between the three Newmark-Beta analyses and the exact mode superposition analysis are shown in Table 2. The first five responses are interface loads between the Array Assemblies (as shown in Figs. 2 and 3) and the Integrated Equipment Assembly (IEA). Responses six and seven are loads between the PV Radiator and IEA. The remaining six responses are loads between the IEA and WP-02 Hardware.

From the ratios in Table 2, it is clear that the results from the Newmark-Beta analyses converge to those of the exact mode superposition analysis. Based on the selected items, percent errors between the first coupled analysis (Newmark-Beta #1) and the exact solution range from 0.3% to 3.3%. The range of percent errors decreases with the second coupled analysis (Newmark-Beta #2). The range is 0.1% to 0.6%. Finally, percent errors for the third coupled analysis (Newmark-Beta #3) decrease further and range from 0.0% to 0.2%. To obtain results within one percent of the exact mode superposition results, at least one half of the integration time step size had to be used for the coupled analysis.

To assess the efficiency of each algorithm, CPU times required to solve for the modal responses were compared. They are shown in Fig. 5. It is clear from Fig. 5 that the exact mode superposition methodology was more efficient than the coupled solution method. To obtain results within one percent of the exact mode superposition results, over four times the amount of CPU time was required for the coupled analysis. It is important to remember that the times shown in Fig. 5 are for one STS liftoff analysis load case. Considering that for a full STS liftoff analysis eleven load cases are analyzed, the savings in CPU time using the exact mode superposition method could be significant.

Conclusions

A methodology has been developed and implemented using MSC/NASTRAN DMAP which allows for the solution of modal equations of motion with initial conditions using the uncoupled solver within module TRD1. In order to illustrate the advantages of using the new exact mode superposition methodology, STS liftoff coupled loads analyses were performed for a real-world engineering application. Comparisons of results showed that while physical responses obtained using the coupled method would converge to those obtained using the exact mode superposition method, a much finer time step was needed for the coupled algorithm. Additionally, for results to be within one percent of each other, the coupled methodology required four times the amount of CPU time as did the exact mode superposition method. Also, when using the exact mode superposition methodology, a convergence study is not needed when selecting integration time steps. Hence, the exact mode superposition methodology which takes advantage of the uncoupled integration routine within DMAP module TRD1 was more efficient and reliable.

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[3]   Flanigan, C.C.; and Manella, R.T.: Advanced Coupled Loads Analysis Using MSC/NASTRAN. Proceedings of the 1991 MSC World Users' Conference, The MacNeal-Schwendler Corp., Los Angeles, CA, 1991, Paper No. 14.

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Table 1. Integration Methods and Time Step Definitions

Integration Method	Time Interval (sec)	Integration Δt (sec)	Frequency of Output
Exact	0.0 - 2.0 2.0 - 6.0 6.0 - 10.0 10.0 - 11.0	0.001 0.001 0.001 0.001	every 100th step every 20th step every 2nd step every 10th step
Newmark-Beta #1	0.0 - 2.0 2.0 - 6.0 6.0 - 10.0 10.0 - 11.0	0.001 0.001 0.001 0.001	every 100th step every 20th step every 2nd step every 10th step
Newmark-Beta #2	0.0 - 2.0 2.0 - 6.0 6.0 - 10.0 10.0 - 11.0	0.0005 0.0005 0.0005 0.0005	every 200th step every 40th step every 4th step every 20th step
Newmark-Beta #3	0.0 - 2.0 2.0 - 6.0 6.0 - 10.0 10.0 - 11.0	0.00025 0.00025 0.00025 0.00025	every 400th step every 80th step every 8th step every 40th step

Table 2. Selected STS Liftoff Analysis Results

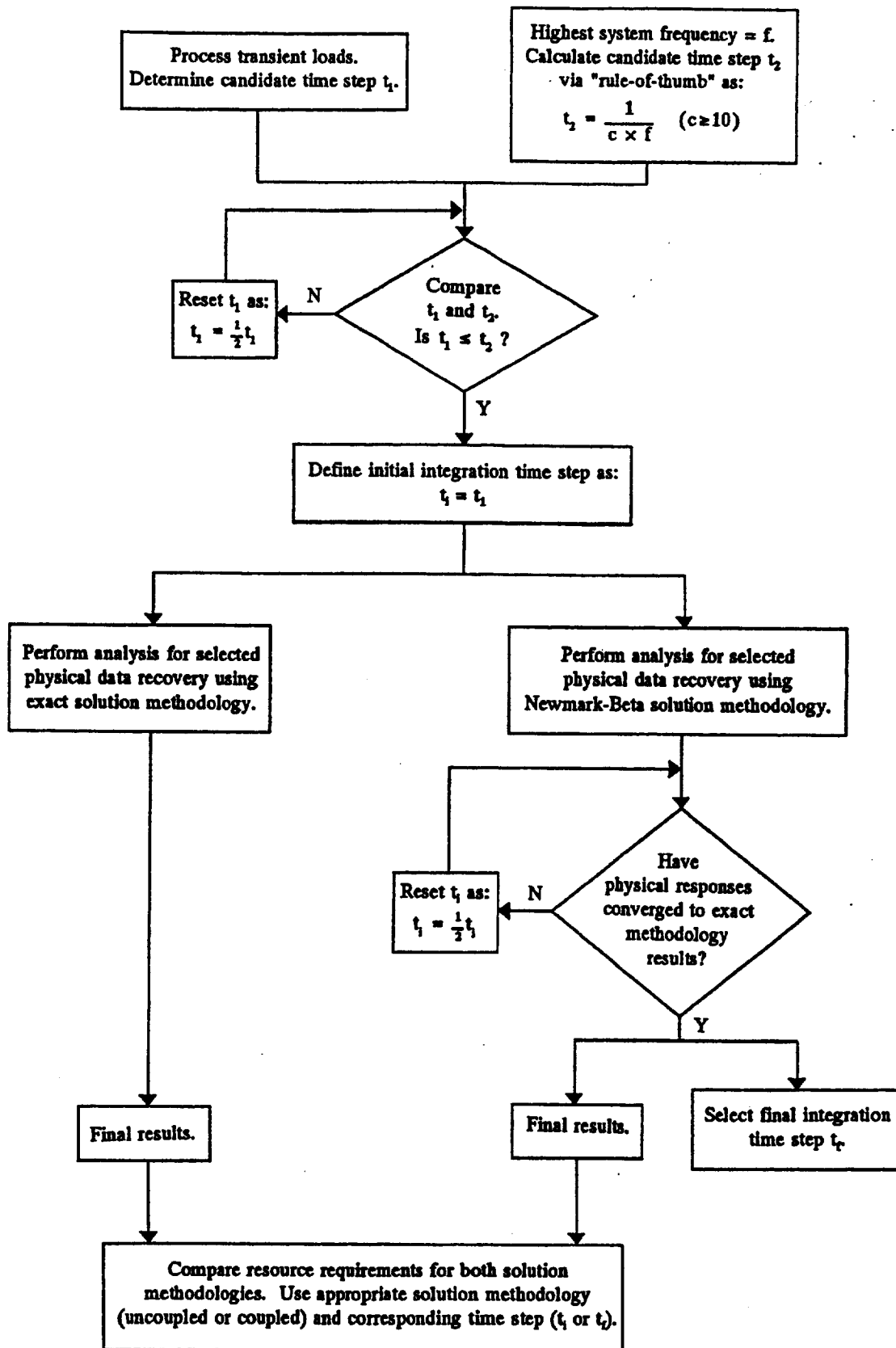| Physical Response	Ratio of Newmark-Beta Value to Exact Value Absolute Maximum Response and Time of Occurrence*		
	Newmark-Beta #1	Newmark-Beta #2	Newmark-Beta #3
1	0.980 (0.930)	0.994 (1.000)	0.998 (1.000)
2	1.014 (1.000)	1.002 (1.000)	1.000 (1.000)
3	0.995 (1.000)	1.001 (1.000)	1.001 (1.000)
4	1.004 (1.000)	1.001 (1.000)	1.000 (1.000)
5	1.033 (0.984)	1.001 (0.984)	1.000 (1.000)
6	0.992 (1.000)	0.998 (1.000)	1.000 (1.000)
7	1.003 (1.000)	1.002 (1.000)	1.001 (1.000)
8	0.983 (1.078)	0.994 (1.000)	1.000 (1.000)
9	1.007 (1.000)	1.002 (1.000)	1.001 (1.000)
10	0.990 (1.000)	0.997 (1.000)	1.000 (1.000)
11	0.994 (1.000)	0.998 (1.000)	1.000 (1.000)
12	0.991 (1.000)	0.998 (1.000)	1.000 (1.000)
13	1.022 (1.000)	1.005 (1.000)	1.001 (1.000)

* Ratio of time of occurrence values shown in parentheses.

| Process transient loads. Determine candidate time step t_1. | Highest system frequency = f. Calculate candidate time step t_2 via "rule-of-thumb" as: $t_2 = \dfrac{1}{c \times f}$ (c≥10) |

Reset t_1 as: $t_1 = \frac{1}{2}t_1$ **N** ← Compare t_1 and t_2. Is $t_1 \leq t_2$?

Y

Define initial integration time step as: $t_i = t_1$

Perform analysis for selected physical data recovery using exact solution methodology.

Perform analysis for selected physical data recovery using Newmark-Beta solution methodology.

Reset t_i as: $t_i = \frac{1}{2}t_i$ **N** ← Have physical responses converged to exact methodology results?

Y

Final results.

Final results.

Select final integration time step t_c.

Compare resource requirements for both solution methodologies. Use appropriate solution methodology (uncoupled or coupled) and corresponding time step (t_i or t_c).

Figure 1.—Procedure for selecting integration time step.

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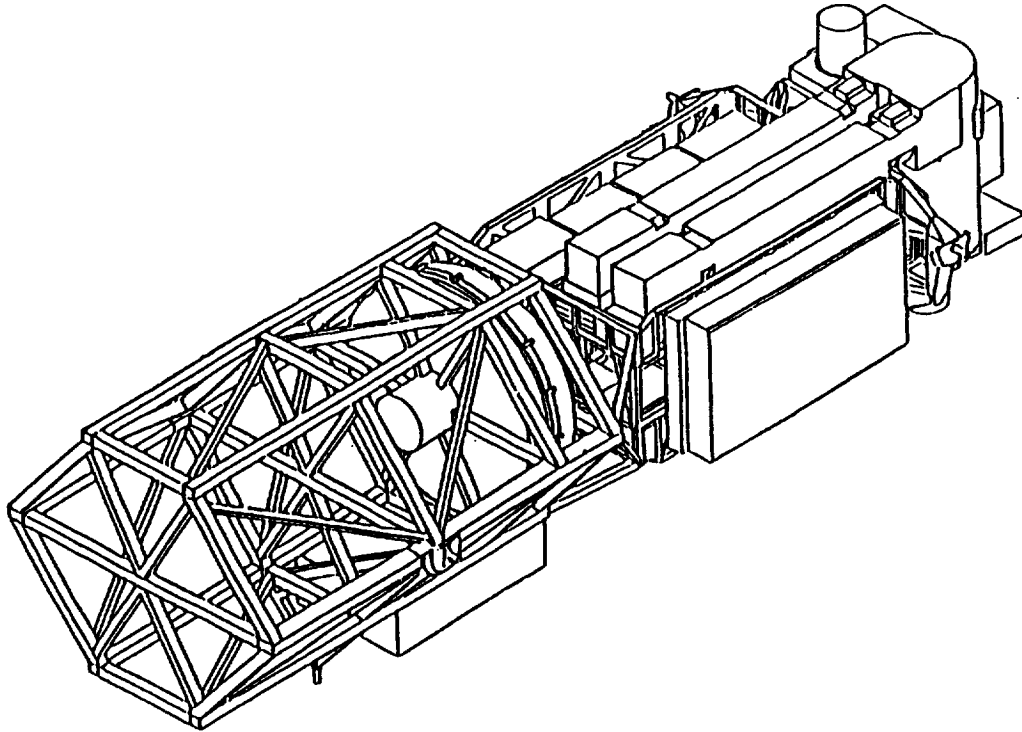
Figure 2.—WP-02/WP-04 Combined cargo element.

PV Array/Mast Canister Assembly (2)

PV Radiator

Integrated Equipment Assembly

WP-02 Hardware
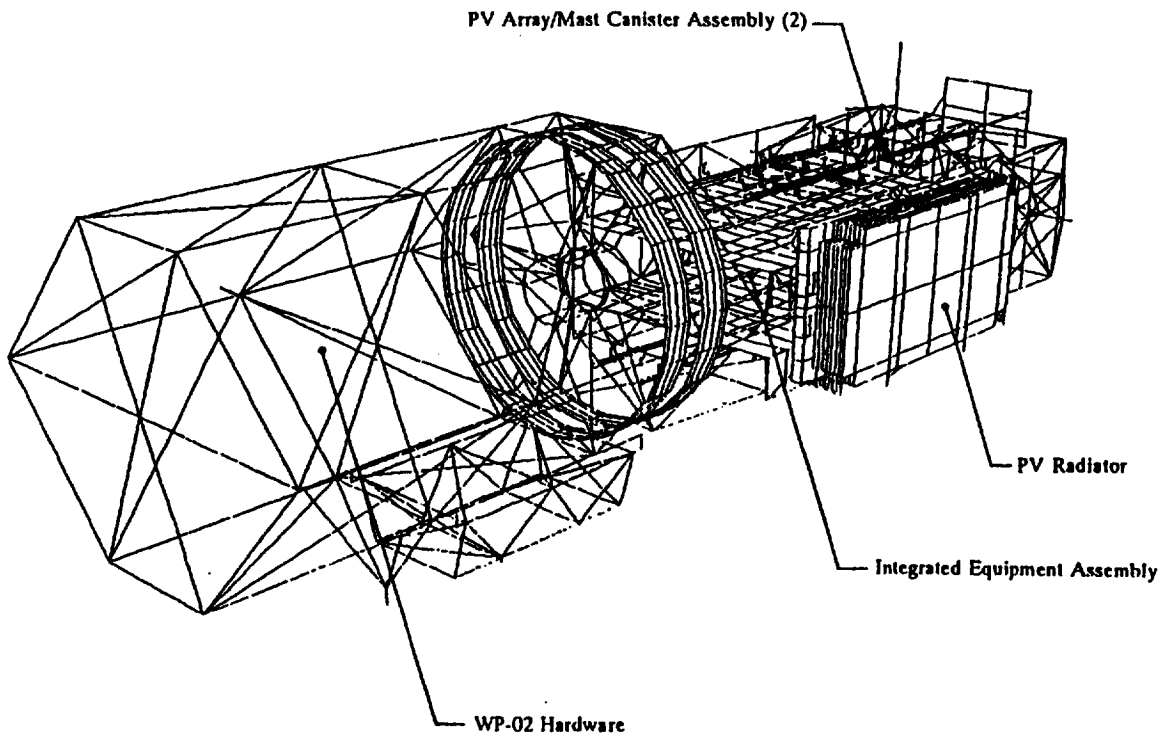
Figure 3.—WP-02/WP-04 Combined cargo element finite element model.
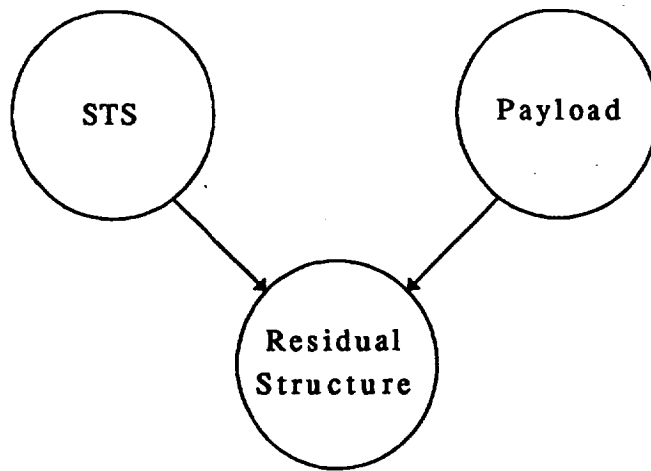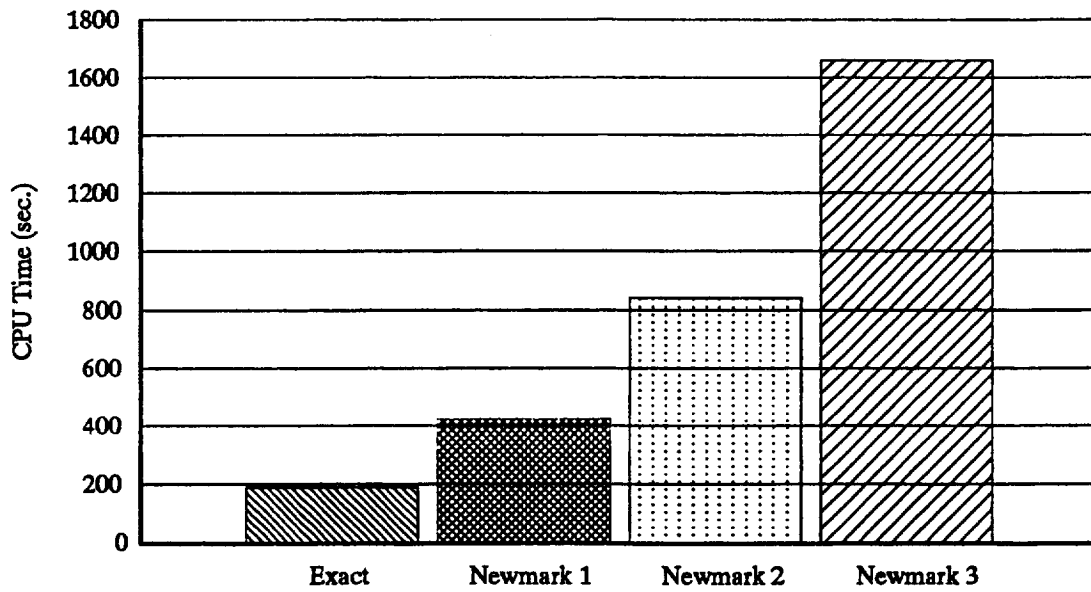
Figure 4.—STS liftoff analysis superelement tree.

Figure 5.—CPU times for modal transient solutions.

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Alan R. Barnett, Omar M. Ibrahim, Ayman A. Abdallah, Timothy L. Sullivan

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Lewis Research Center
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