UPDATED DYNAMIC ANALYSIS METHODS FOR THE SPACE SHUTTLE SOLID ROCKET MOTOR

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ABSTRACT

The RSRM dynamic models and analysis procedures were recently updated to take advantage of improvements in computer hardware and software performance. Many new and enhanced features of MSC/NASTRAN were exercised including sparse matrix routines, Lanczos eigensolver, enhanced superelements, and residual vectors. The models and analysis procedures were migrated to Windows NT workstations to take advantage of the price/performance ratio of these platforms.

The methods upgrade for the RSRM dynamic models has significantly improved ease of use, dramatically reduced computer run times, and minimized the need for custom codes. Important features of the upgraded methods will be presented in the paper. Computer run times using NT workstations will be compared to original analyses performed on Cray mainframes.

INTRODUCTION

Thiokol and its subcontractors developed detailed models of the redesigned solid rocket motor (RSRM) during the Space Shuttle redesign program (1986-1988). For dynamic analysis, 3-D finite element models of the complete RSRM were created to assess global responses and to provide boundary conditions for detailed analysis of local responses including field joint gap opening.

The original RSRM dynamic models used the best modeling techniques and analysis methods available at that time. Advanced analysis methods including image superelements and custom computer codes for transient analysis were employed for accuracy and efficiency. However, even with these advanced features, the models were sufficiently large that computer run times were substantial (many CPU days on Cray mainframe computers). In addition, the analysis process required a long sequence of computer runs, providing many opportunities for user error and incorrect results. Finally, the custom computer codes required regular upgrading and maintenance along with specialized user training to remain usable.

Since the original RSRM development effort, computer hardware and software capabilities have increased significantly. MSC/NASTRAN has changed in many aspects including the DMAP language and database structure. Computers are much faster and cheaper. Operations that formerly required a Cray mainframe can now be handled by desktop workstations. The combination of improved analysis software methods and computer hardware capabilities provided the opportunity for a major update to the analysis process used for the RSRM dynamic models.

The objective of this effort was to update the RSRM dynamic analysis to improve ease of use, reduce turn-around time, and minimize future maintenance requirements. The project focused on the following areas:

- Update all techniques to be compatible with the current version of MSC/NASTRAN
- Make use of computing and methodology improvements
- Simplify analysis procedures to take advantage of commercial software and minimize the use of specialty custom codes

ORIGINAL PROCESS

The RSRM models and processes were implemented using state-of-the-art methods available in the mid-1980's. Important process features are summarized in following paragraphs.

- **Component Model Files**. The bulk data file was divided into multiple smaller files to simplify model development and configuration management. Typical files included grid/element bulk data, element/material properties, applied loads, and superelement definition. A custom program called MERGE was used to assemble the component files into a single NASTRAN input deck.
- **Redundant Interfaces**. A single set of grids was used at the superelement interfaces to simplify the superelement definition. This caused the interface grids to appear in two or more component bulk data files. A custom program called REDUN was developed to eliminate redundant grids and other duplicated information from the assembled NASTRAN input deck.
- **Image Superelements**. Image superelements were used to reduce modeling time and minimize computer re-

source requirements. Each motor segment was created using a 60° primary superelement and five rotated image superelements. The aft skirt was modeled using a 180° primary superelement and a mirror image superelement. The use of image superelements significantly reduced CPU and disk storage requirements. However, correctly applying loads and displaying results using image superelements was very difficult. A custom program called SEMCOMB was used to combine the superelement modes into unified datasets and to perform special geometry and numbering operations for the image superelements.

- **Mesh Transition**. Very small solid elements were required to represent the propellant in the field joint models near the joints. Larger elements were used in the segment models. MPC equations were used to define the constraint equations that would cause the fine and coarsh mesh models to move in a compatible manner. A custom code called EPOXY was developed to calculate the MPC coefficients based on element geometry.
- **Normal Modes**. The RSRM component models were considered very large at the time. The only practical method available to calculate component modes was to use Generalized Dynamic Reduction followed by an eigensolution using the Givens method. This approach appeared to work well although there was some concerns regarding the high modal density caused by large numbers of propellant modes.
- **Transient Analysis**. A significant portion of the RSRM dynamic responses are caused by internal pressure within the motor case. Therefore, it was imperative to use mode acceleration data recovery to obtain accurate case stresses and gap response. Since the MSC/NASTRAN mode acceleration method did not apply to upstream superelements, custom codes including EZTRAN and DRMEXT were required to form data recovery matrices, perform modal transient analysis, and recover accurate responses using the mode acceleration method.
- **Databases**. Separate NASTRAN databases were used for each component model. This provided excellent flexibility for storing and accessing the data. However, no automatic restart capability was available, and the user was responsible for providing and upgrading the appropriate rates.

All of these procedures worked well. However, many steps were required to process the component models, assemble the system model, apply loads, develop data recovery matrices, perform transient analyses, and recover responses. A long series of runs had to be performed correctly to obtain valid answers. In addition, engineers had to be trained in how to use the custom methods and how to recognize if any step had not executed successfully. Finally, the procedures used a large number of custom codes and DMAP alters which required maintenance for each update of MSC/NASTRAN or computer system or platform change.

UPDATED PROCESS

The objective of this effort was to update the RSRM dynamic analysis to improve ease of use, reduce turn-around time, and minimize future maintenance requirements. The project focused on the following areas:

- Update all techniques to be compatible with the current version of MSC/NASTRAN

- Make use of methodology and computing improvements
- Simplify analysis procedures to take advantage of commercial software and minimize the use of specialty custom codes

All objectives were successfully achieved by this project. Significant accomplishments are described in the following paragraphs.

- **Component Model Files**. The component model files were retained as in the original process. The component files were assembled into the NASTRAN input using the INCLUDE statement. The custom code MERGE was no longer required.

- **Sparse Matrix Solvers**. The improved sparse solvers in MSC/NASTRAN Version 70.5 were used for all analyses. The amount of memory required was readily available on typical engineering workstations. The sparse solvers significantly reduce solution times compared to the traditional matrix operations in MSC/NASTRAN.

- **Solid Element Transition**. The transition of coarse to fine propellant elements was converted from MPC equations to RBE3 elements. The RBE3 elements automatically calculated the constraint coefficients based on geometry. This approach eliminated the need for the custom EPOXY program and also provided improved numerical conditioning.

- **Superelement Interfaces**. The superelements were renumbered such that different interface grids were used in each component models. The component models were connected using RBE2 elements. Having separate grids at the interface eliminated the need for the custom code REDUN to eliminate redundant grids at the superelement interfaces.

- **Image Superelements**. The image superelements were physically replicated to form complete superelements. This greatly simplified the superelement tree, expedited the input deck setup, and improved results display. Computing time and disk storage requirements for the standard superelements were well within modern standards for large models.

- **Normal Modes**. The Generalized Dynamic Reduction method was replaced by the Lanczos eigensolution method. The Lanczos approach efficiently calculated modes for the large RSRM models including high modal density.

- **Residual Vectors**. The new residual vector released in MSC/NASTRAN V70 provided dynamic response accuracy comparable to the traditional mode acceleration method. However, the residual vector method operates on upstream superelements as well as the residual structure. The residual vector allowed the complete transient analysis including data recovery to be performed within MSC/NASTRAN. This eliminated the need for custom transient analysis programs and related codes.

- **Databases**. A variant of the multi-master database technique was used to allow each component to be processed in a separate run and then combined into the residual structure. While this eliminated the capability for an automatic restart, it provided greater user flexibility and greater reliability for the data.

RSRM GLOBAL MODEL RESULTS

The new dynamic analysis procedures are illustrated using the RSRM global model shown in Figure 1. This model is very detailed and includes over 500,000 dynamic DOF.

Component modes were calculated using standard superelement methods. Using standard superelements instead of primary and image superelements allowed the use of a single level superelement tree as shown in Figure 2. Each component was analyzed in a separate run to verify correct results prior to continuing to the next component. However, “production” runs could be performed with several or all components analyzed in a single run.

System modes and transient responses were calculated in the next runs. Special database commands shown in Figure 3 were used to access the databases from the component runs. In addition, PARAM,SERST was set to ‘MANUAL’ to perform a manual restart.

Typical acceleration histories are shown in Figure 4. These results were typical of those for a Space Shuttle liftoff analysis and were essentially identical to those calculated using the previous methods. Typical case stress results are shown in Figure 5. The case stresses closely follow the pressure rise and approximately match the static steady-state response caused by the internal pressure, indicating that the residual vector method is providing accurate responses for upstream superelements.

Run times (CPU and wall clock) are listed in Table 1. The previous runs were performed using MSC/NASTRAN V65A on a Cray X-MP, and the current runs were performed using MSC/NASTRAN V70.5(R4) on a Windows/NT workstation with dual Pentium II 366 MHz CPUs. The CPU usage on the Cray X-MP was lower than the current NT workstation. However, the Cray wallclock time was approximately the same as the NT workstation due to the need to offload and reload the large databases from disk and tape storage.

CONCLUSIONS

The objective of this effort was to update the RSRM dynamic analysis process to improve ease of use, reduce turn-around time, and minimize future maintenance requirements. All objectives were successfully achieved by this project.

As a result of this project, the processing of the RSRM dynamic models has been significantly simplified. The complete modal and transient analysis can be performed in just one or two computer runs compared to the extensive series of runs needed by the previous methods. The analysis of the RSRM detailed global model can be completed in less than one day on an NT workstation compared to many days on a Cray mainframe. Only one MSC/NASTRAN rigid format alter is required, and the need for custom codes has been completely eliminated.

In conclusion, this project has greatly simplified and streamlined analysis processing using the RSRM dynamic models. These models can now be used much more quickly and effectively to support Space Shuttle operational activities and future studies.

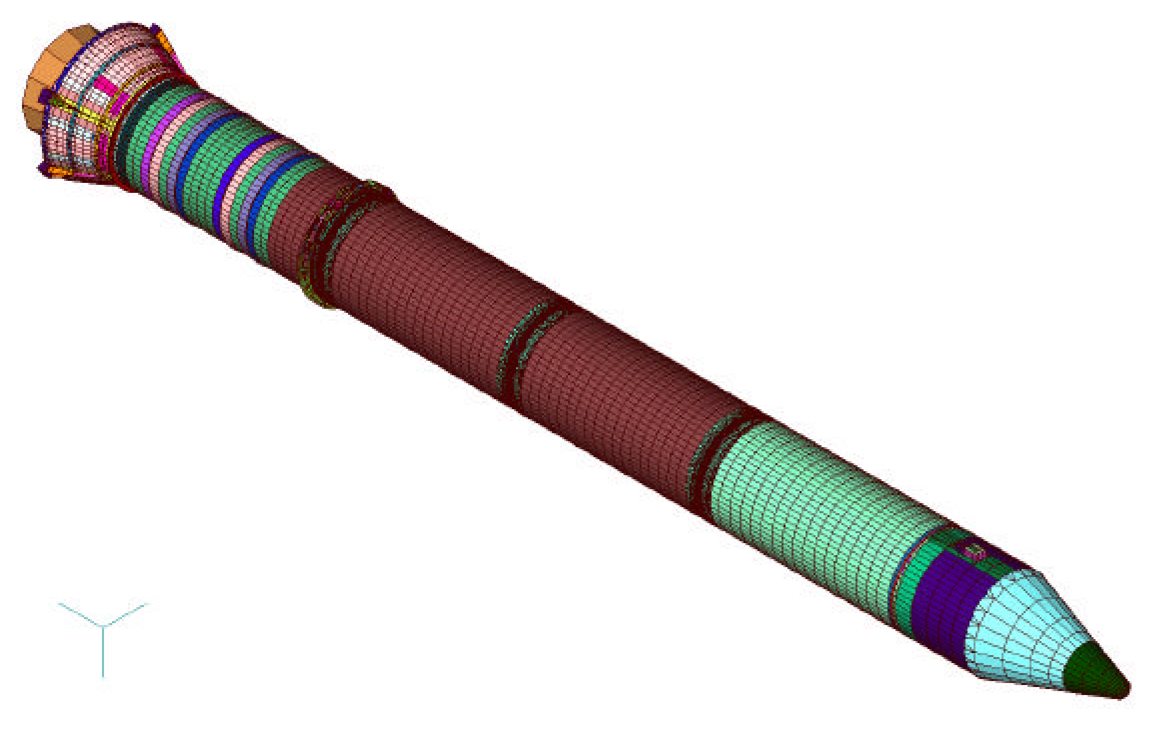

Figure 1. The global model of the Space Shuttle redesigned solid rocket motor (RSRM) contained over 500,000 dynamic DOF

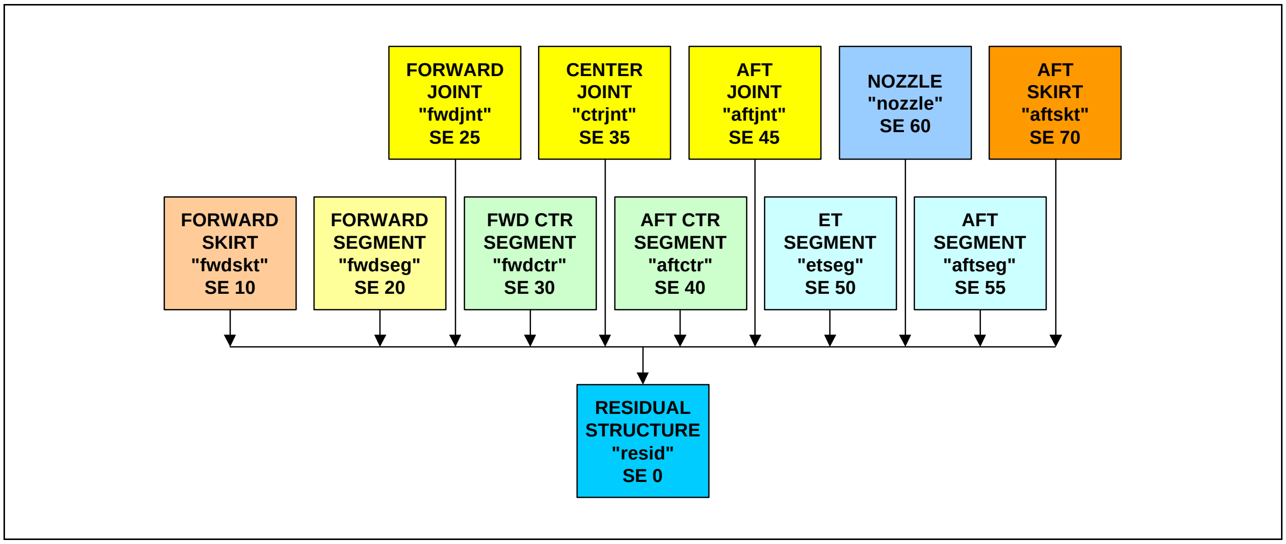

Figure 2. Image superelements were replaced by standard superelements to provide a single level superelement tree.

```
NASTRAN  BUFFSIZE=8193 SYSTEM(166)=0
$
$  System modes database
$  ---------------------
$
ASSIGN MASTER='h:\sys_modes.MASTER' DELETE
ASSIGN DBALL ='h:\sys_modes.DBALL'  DELETE
$
$  Component databases
$  -------------------
$
ASSIGN FWDSKTM='g:\fwdskt.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=10 OR SEID=10) LOGI=FWDSKTM
$
ASSIGN FWDSEGM='g:\fwdseg.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=20 OR SEID=20) LOGI=FWDSEGM
$
ASSIGN FWDJNTM='g:\fwdjnt.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=25 OR SEID=25) LOGI=FWDJNTM
$
ASSIGN FWDCTRM='g:\fwdctr.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=30 OR SEID=30) LOGI=FWDCTRM
$
ASSIGN CTRJNTM='g:\ctrjnt.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=35 OR SEID=35) LOGI=CTRJNTM
$
ASSIGN AFTCTRM='g:\aftctr.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=40 OR SEID=40) LOGI=AFTCTRM
$
ASSIGN AFTJNTM='g:\aftjnt.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=45 OR SEID=45) LOGI=AFTJNTM
$
ASSIGN ETSEGM='g:\etseg.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=50 OR SEID=50) LOGI=ETSEGM
$
ASSIGN AFTSEGM='h:\aftseg.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=55 OR SEID=55) LOGI=AFTSEGM
$
ASSIGN NOZZLEM='g:\nozzle.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=60 OR SEID=60) LOGI=NOZZLEM
$
ASSIGN AFTSKTM='g:\aftskt.MASTER'
DBLOCATE DATABLK=* WHERE (PEID=70 OR SEID=70) LOGI=AFTSKTM
$
```

Figure 3. Special FMS commands were used to access the component databases while providing read-only access for file integrity.

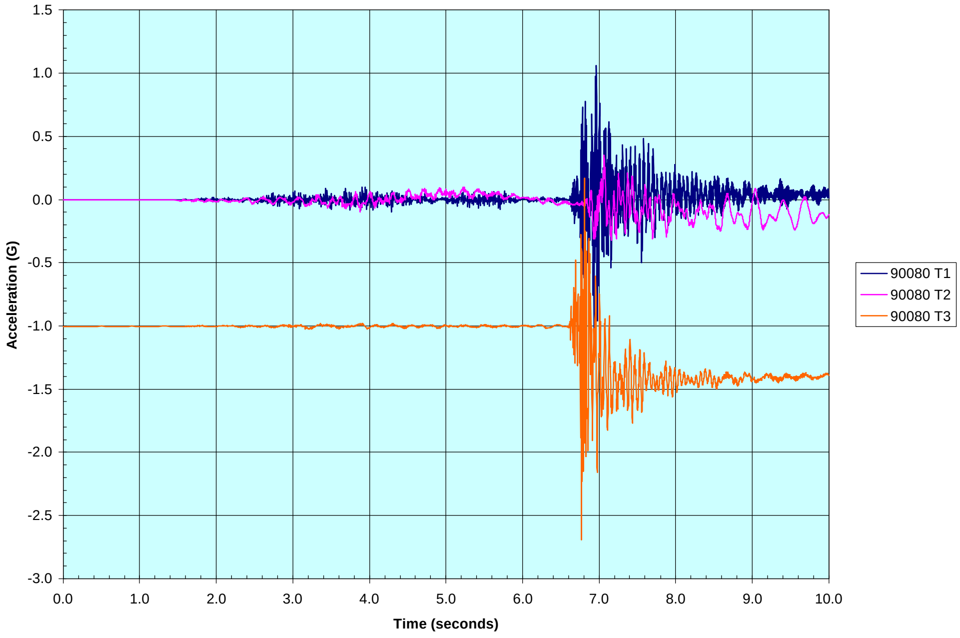

Figure 3. Dynamic accelerations calculated using the updated procedures closely matched those from the original analyses.

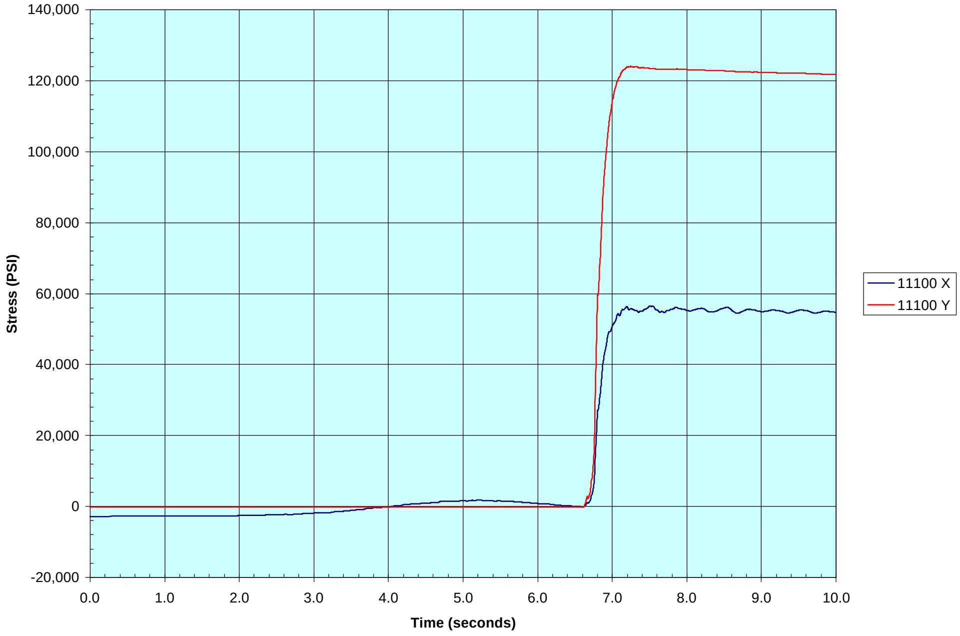

Figure 4. Close agreement of case stresses to the internal pressure indicated that the residual vector method provided accurate transient responses.

Table 1. Wall clock times using the new procedures on an NT workstation were comparable to those using V65A on a Cray X-MP mainframe.

Component	V65A / Cray X-MP		V70.5 / NT PII 366 MHz	
	CPU (Sec)	Clock (Min)	CPU (Sec)	Clock (Min)
Forward Segment	2,730	72	4,999	107
Forward Joint	1,422	90	6,551	193
Fwd Center Segment	2,730	72	4,681	101
Center Joint	1,422	90	6,296	175
Aft Center Segment	2,730	72	4,798	104
Aft Joint	1,422	90	8,373	239
ET Segment & Ring	1,568	123	4,627	126
Aft Segment	3,471	243	10,242	249
Aft Skirt	850	22	371	8
Residual Structure	3,593	519	13,618	302
TOTAL	21,938	1,393	64,556	1,603
	6.1 CPU Hours	23.2 Clock Hours	17.9 CPU Hours	26.7 Clock Hours