

A STRATEGY FOR INTEGRATING A LARGE FINITE ELEMENT MODEL: X-33 LESSONS LEARNED

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ABSTRACT

The X-33 vehicle is an advanced technology demonstrator sponsored by NASA. For the past three years the Structural Dynamics & Loads Group of NASA's Marshall Space Flight Center has had the task of integrating the X-33 vehicle structural finite element model. In that time, five versions of the integrated vehicle model have been produced and a strategy has evolved that would benefit anyone given the task of integrating structural finite element models that have been generated by various modelers and companies. The strategy that has been presented here consists of six decisions that need to be made. These six decisions are: purpose of model, units, common material list, model numbering, interface control, and archive format. This strategy has been proved and expanded from experience on the X-33 vehicle.

INTRODUCTION

The responsibility for large structures rarely rests in the hands of a single institution any longer. The responsibility is now being spread across a larger number of industry partners. So too is the responsibility for the structural finite element models used for assessing these structures. This broad effort often needs to be refocused into an integrated model that reflects characteristics of the full system. This is the task of the model integrator.

Attempts have been made in the past to provide tools to the model integrator to simplify this task. ALAS¹ is an example of a tool that attempted to simplify some of the analytical aspects of the integration task. Many of today's computer-aided

engineering or CAE packages have various tools and degrees of success supporting this process. MSC/SuperModel is one of the latest tools to put forth a system for simplifying this process^{2,3}. It itself is based on tools developed in house at the old McDonnell-Douglas Aircraft Corporation similar to in-house tools developed at many companies. Even with these current and developing tools most of the modelers involved in the project likely use different CAE packages. This offers its own challenges to the integrator.

For the past three years the Structural Dynamics & Loads Branch of NASA's Marshall Space Flight Center has had the task of integrating the X-33 vehicle structural finite element model. In that time, five versions of the integrated vehicle model have been produced. A great number of lessons were learned in this process. Presented here is a strategy that, if used at the outset of the project, will pave the way for a smooth integration. This strategy would benefit anyone given the task of integrating structural finite element models that have been generated by various modelers and companies. This strategy also provides benefits regardless of the tools used to help the integrator in this task.

THE X-33 MODEL INTEGRATION PROBLEM

The X-33 vehicle is an advanced technology demonstrator sponsored by NASA. The X-33 program will demonstrate, in flight, the new technologies needed for a reusable launch vehicle using a half-scale prototype. NASA has selected Lockheed-Martin Skunkworks to design, build, and fly the X-33 test vehicle. The industry team, with Lockheed-Martin Skunkworks as lead, includes Lockheed-Martin Michoud, B.F. Goodrich (previously Rohr), Boeing Rocketdyne, and NASA.

The X-33 has a complicated and highly coupled structural design. It consists of a liquid oxygen tank sitting on top of a pair of side-by-side liquid

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hydrogen tanks. Behind and in-between the hydrogen tanks are the two aerospike engines. Over all of this is a complex aeroshell structure that provides thermal protection and the aerodynamic shape of the lifting body. The canted and vertical fins and body flaps are also attached to the thrust structure.

In order to assess the design, an integrated vehicle finite element model was required to determine internal loads. These internal loads were derived from externally applied forces in both static and transient dynamic loads analyses. The required model was generated from individual major structure models obtained from across the industry team. Models of the liquid hydrogen tanks, thrust structure, intertank, and landing gears were provided by Lockheed-Martin Skunkworks. The liquid oxygen tank model was provided by Lockheed-Martin Michoud. The Aerospike engine model was provided by Boeing Rocketdyne. B.F. Goodrich provided models of the canted fin control surfaces. The Structural Dynamics & Loads Branch of NASA's Marshall Space Flight Center had the task of modeling the aeroshell, body flap control surfaces, canted and vertical fins, and the rotating launch mount. The Structural Dynamics & Loads Branch also had the task of integrating the various models into the full vehicle model.

The integrated vehicle model that resulted has had five versions. Four complete loads analysis cycles have been completed. These include static pre-launch, ascent, descent, landing, and transient liftoff analyses. A fifth loads cycle is underway. The models have also been used to assess dynamic characteristics for flight control analyses. The model grid count peaked at 29427 grids for load cycle 4 and is now down to 20400 grids for load cycle 5 after a concerted effort to reduce the model size.

STRATEGY FOR MODEL INTEGRATION

The strategy presented here consists of six decisions that need to be made at the outset of the project. These decisions, once made and agreed to by the modeling team, will pave the way for a smooth model integration. These six decisions are: purpose of model, units, common material list, model numbering, interface control, and archive format. Each is discussed in detail below.

Purpose Of Model

The first decision to be made is the purpose of the model. Is it a stress model? Is it a loads model? A dynamics model? This decision drives many of the following decisions. In particular it defines the scope of the model and therefore the approach to the modeling. It would also have a direct impact on the size of the model. The effort for X-33 was to develop a model that would be used to recover internal element forces for use by stress analysts. It was never intended to recover stresses as this would have led to a model that would be all but impossible to run. It was also meant to adequately represent elastic modes from 0 to approximately 25 HZ so that liftoff transient loads could be recovered. These dynamic characteristics were also to be used for control stability studies and POGO analyses. During the entire development of the model it was a continual challenge to balance the need for accurate forces (not stresses) and dynamics and still have a reasonably sized model. Accommodations also had to be made, both in increased and decreased fidelity, when it was decided the model would also be used for flutter analyses.

It should be noted here, that on the X-33 project two model "styles" existed. One style of modeling consisted of modeling the structure the way it was intended to work. For example, modeling web caps with rod elements because they were primarily intended to carry axial load. The other style modeled the structure the way it was drawn or built in order to verify the assumptions used in design. For example, the web caps were modeled with bar elements to verify that the axial load was the only significant load. Every modeler uses a combination of these styles. The reasons include preference, economy, time, and maturity of design. There is little expectation that the modeling can be controlled to the point of requiring a consistent style. However, the model integrator needs to be aware of these styles so that any issues that come up because of them can be quickly recognized and settled.

Units

The units of measure the model will use need to be decided. This could be of great importance if the model is a joint venture between European and US modelers. Even if the standard units used by the modelers are similar, care should be taken, especially with mass vs. weight units. While in the US most aircraft modelers commonly use inches, density poses a problem. Many modelers use weight density but also, many modelers use mass density. The desired units for the integrated model

should be decided very early so the individual modelers can accommodate this. This was not done on X-33, so a number of models had to have their densities converted. Fortunately all models were in inches.

Common Material List

The next things to determine are material properties. It would be very advantageous to establish a common material list for use by all the modelers. The advantage would be a consistent set of properties between modelers and therefore no redundancy in material definitions. Even though the materials might be standard there are many variations in alloys and thermal characteristics. This list would obviously grow and change as the design evolves but it should be a simple matter to provide regular updates. Even if a particular model needed some specialized properties it would start with a common base.

In conjunction with the common materials list, the ambient temperature of each model should be defined. This could have a large effect on the material properties used for that model. For example composite material properties are much more dependent on temperature than metals, but even aluminum has significant changes at cryogenic temperatures such as the liquid oxygen tank for the X-33. Also thermal protection materials drastically change properties over their expected temperature ranges. Several different material definitions may be necessary for the same material because of its use in different areas. For example a composite material may be used in a cryogenic liquid hydrogen tank and also a hot thermal protection support beam and therefore have two different material definitions. A common reference temperature and units for coefficients of thermal expansion should also be established to facilitate a thermal contraction or expansion assessment.

The use of a common materials list would also allow for easier changing of material properties for assessment of different temperature profiles of the integrated model. For example the ascent temperature profile of the X-33, and therefore its material properties, may be drastically different from the descent profile. You may therefore have a different common material list for each temperature profile with the same material identification. These lists could then be exchanged to assess the model for the different profiles.

Invariably, somewhere, the model will use a "stiff" bar or plate where an RBAR won't do or use stiff

springs to recover interface loads in the global coordinate system. It would be good to define these materials and properties in the common material list also, so all the modelers could be consistent and reduce redundant definitions.

The value of the MSC/NASTRAN parameter K6ROT for drilling stiffness in shell elements should be decided early. Some modelers depend on a large value of K6ROT to alleviate drilling stiffness problems. Others depend on zero or low values of K6ROT to allow some freedom in this direction. Even if you can specify different K6ROT parameters for different Super Elements it is a good idea to specify a default value so the modelers may accommodate it with other techniques.

Neither the common materials list or temperature profiles were established for the X-33 model and this has caused a certain amount of aggravation throughout its evolution. Such a list would also be of great benefit to model correlation efforts at a later date. It may still be necessary to go back and establish this list but it would have been much easier to have established it from the start.

Model Numbering

Assigning node number ranges to the different models is fairly common practice. You may want to specify a target number of grids to help limit the size of the model, but be sure to allow adequate room for inevitable growth. Enforce the numbering not only on nodes but also elements, properties, rigid elements and multi-point constraints. Rigid elements and multi-point constraints can cause difficulties. MSC/NASTRAN and MSC/PATRAN sometimes treat them as elements and sometimes treat them as separate entities. This can particularly be a problem if you later decide to use Super Elements. Older versions of MSC/NASTRAN would allow an element and a rigid element to have the same number in a standard analysis but not in a Super Element analysis. To be safe, make sure their numbering is exclusive of the elements. The material numbering should be from the common material list but if a special material is needed enforce the numbering range. And finally, make the ranges different enough that you can easily identify the model an element, node, or property belongs to.

Interface Control

If at all possible an Interface Control Document or ICD should be established for the different model pieces. This is a document that defines the

interface geometry and loads between different portions of the model or structure. For the most part this data is already contained in structural ICD's. For X-33 this was true for interfaces between companies such as B.F. Goodrich and Lockheed-Martin Skunkworks or Lockheed-Martin Michoud and Lockheed-Martin Skunkworks. Lockheed-Martin Michoud's ICD (Figure 2) was particularly well done and was invaluable in interfacing the liquid oxygen tank model with other models. Much of the X-33 was designed within the same company and did not have a structural ICD. It would be very beneficial to establish such ICD's for the purposes of the models even if they are not rigidly controlled documents. They might also help define better divisions of responsibility for the model pieces. An example for X-33 would be the aeroshell ring frames over the liquid hydrogen tanks. The ring frames modeling responsibility belonged to the aeroshell modeler and the tank modeling responsibility to another. Since the ring frames attached continuously to the tanks a great deal of coordination was required to make the model meshes match. A better approach might have been to let the tank modeler model the ring frames and define an ICD for the frame to aeroshell interface. This would still require coordination but the interface would be better defined and more along structural lines rather than model meshes.

In instances where the interface between structures should only pass loads or allow compliance in certain directions the ICD should carefully indicate which side these releases are modeled. The structural ICD should make this clear, however many modelers that are only concerned with one side of the interface will not make any provisions for special releases except through model constraints. These constraints are then lost upon integration and it is left to the integrator to fix the problem, usually with springs or rigid elements. This is not necessarily the most efficient method. This problem occurred with regularity on the X-33 project.

Archive Format

The format for storing and transmitting the model data needs to be decided. For X-33, this was decided to be the MSC/NASTRAN bulkdata. This decision was made for two primary reasons. First, because the modeling effort spanned several companies that used various computer-aided engineering or CAE packages, even different versions of those packages, the bulkdata was deemed the most portable. MSC/NASTRAN was the most common denominator. Secondly, even

though the CAE translators to MSC/NASTRAN are continually improving, they are not perfect. Since these models would be passed back and forth many times and passed through CAE translators multiple times it was decided that the bulkdata would be the trusted copy. Any modifications that were made with the help of the CAE packages would be output to MSC/NASTRAN but then text edited into the archive bulkdata format. In fact, for X-33, most errors between model versions were traced back to passes through the CAE packages where beam orientations, section properties, and material definitions were compromised. Bulkdata comments could also be preserved with this cut and paste method.

For X-33, it was also decided that the separate models would remain in separate files and assembled using "include" statements in the MSC/NASTRAN analysis file. This provided ease of updates for portions of the model that were in various stages of flux and design. A sub model's included bulkdata file could easily be replaced with a new one as updates were made without affecting the rest of the model. Also, had the common material list been used this would be a convenient way of using it. This decision, as beneficial as it was, created one problem. On the one hand, MSC/NASTRAN does not allow duplicate grid definitions. This prohibited having grid definitions in both bulkdata files for models that interfaced. On the other hand, the CAE packages cannot read in the bulkdata for a sub model without this grid definition. For example, SDRC IDEAS would not read in any of the file if there was such an error while MSC/PATRAN would not read in affected elements but would read the rest of the file.

One suggestion for handling this problem was that each sub model have completely unique grid numbers and then have an additional interface file that contained connecting springs or rigid elements. This could be an effective method for a relatively simple model with few interfaces but for this highly coupled structure the cost of additional grids and elements would be prohibitive. Also it would be very difficult to ensure absolutely coincident grid points that are required for this method to work correctly.

The solution decided on for X-33 was that within a sub model bulkdata file all grid definitions that interfaced with other sub models would be placed in the bottom of the bulkdata file where they could be easily found (Figure 3). Further, the bulkdata files would be considered in an upstream/downstream fashion similar to Super

Elements. The sub model bulkdata files were named with a preceding number to facilitate this upstream/downstream ordering. An interface grid was defined once in an upstream bulkdata file. When it was referenced in a downstream bulkdata file its definition would be commented out with a unique integration comment such as "\$INTEG \$". Thus when all bulkdata files were included in the MSC/NASTRAN analysis file no duplicate grid definitions would result. If it was necessary to read a bulkdata file into a CAE package or have a checkout analysis done by itself then all occurrences of the "\$INTEG \$" comment would be changed to nothing in a text editor first.

USE OF MSC/PATRAN IN MODEL INTEGRATION

MSC/PATRAN was the CAE package used for the model integration. This was a difficult task made relatively easy by several of MSC/PATRAN's features associated with creating and displaying groups. Lockheed-Martin Michoud reported great difficulty completing similar tasks with SDRG IDEAS. In particular, MSC/PATRAN offered a unique benefit to this integration process. With the sub model bulkdata files defined as they were, they could be read into MSC/PATRAN to form an integrated model database as long as the files were read in the proper order. This could be done without having to edit out the "\$INTEG \$" comments. In addition this process was vastly aided by the use of a journal file. The journal file was constructed to create a group, set it as default, and then read the bulkdata and repeat for the next file. With this journal file it was extremely easy to reconstruct integrated model databases for viewing results. It was also very easy to establish an X-33 template for use by other engineers. For the other companies that used MSC/PATRAN, but had different versions on different machines, this was a convenient way of providing them with a database.

PITFALLS ENCOUNTERED WITH MSC/PATRAN

The largest MSC/PATRAN pitfall encountered lies in the association, in the database, of the beam orientation vectors with the property rather than the element. The X-33 model has a large number of beam elements with the same cross sectional properties but different orientations. The orientations were not easily defined by a MSC/PATRAN field so a different property was required for each while defining them in the database. These were later text edited, in the

bulkdata file, to reference the same property card. On reading this bulkdata file back into MSC/PATRAN, the property remained a single property entry with a MSC/PATRAN spreadsheet field for the orientation. This was convenient when checking beam properties. However, when it was desired to add a new beam based on the existing property the output beam orientation was undefined and had to be text edited later in the bulkdata file.

Another pitfall was described in Section 3.5 above, regarding translation between the CAE package and the bulkdata. Even MSC/PATRAN and MSC/NASTRAN had this problem, although it was worse with other CAE packages. In fact, for X-33, most errors between model versions were traced back to passes through the CAE packages where beam orientations, section properties, and material definitions were compromised.

One other pitfall occurred regarding the translating of the bulkdata into MSC/PATRAN. This problem came with the switch from MSC/PATRAN 6.2 to MSC/PATRAN 7.0. The model contained a set of multi-point constraints or MPC's that were defined on multiple MPC cards but having the same MPC number. MSC/NASTRAN handles this very well. MSC/PATRAN reads each of the separate cards and then internally offsets the MPC id for each one. This particular offset is not user controllable. In version 6.2 this offset is fixed at 1 which caused no problem. In version 7.0 the fixed offset was changed to 10000. This caused the offset numbers to clash with other rigid element entities. Fortunately the journal file could be reordered somewhat to avoid this problem.

CONCLUSION

The task of integrating a structural finite element model that has been developed by several modelers from several companies is challenging. This task has unquestionably benefited from all the tools made available through the currently available CAE packages. There are, however, strategies that can be brought to bear that can smooth the process greatly. Even with many of these strategies now being included in the next generation of CAE packages the model integrator's understanding of them is essential. This is particularly true with the variety of sources of models being integrated. These strategies are best used early in the project to lay a good foundation for integration. A strategy has been presented here that consists of six decisions that need to be made. These six decisions are: purpose of model, units, common material list, model numbering, interface control, and archive

format. This strategy has been proved and expanded from experience on the X-33 vehicle.

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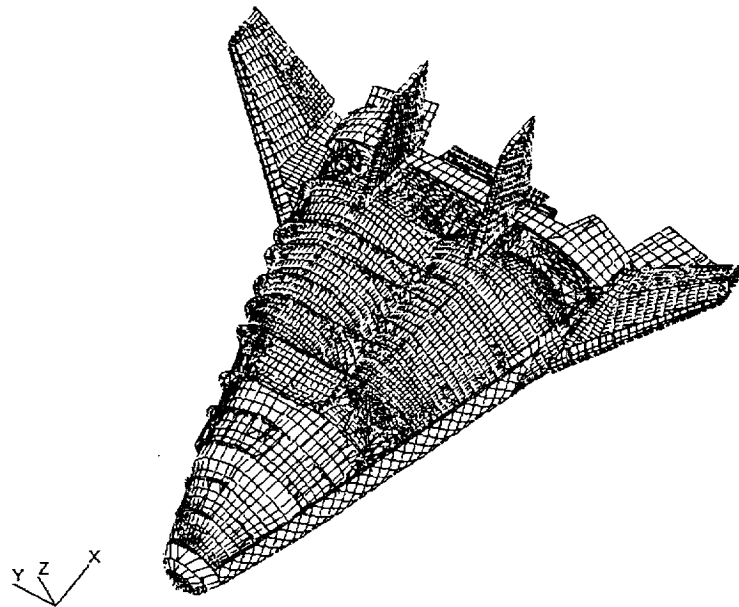


Figure 1. Cut-away View of X-33 Structural Finite Element Model

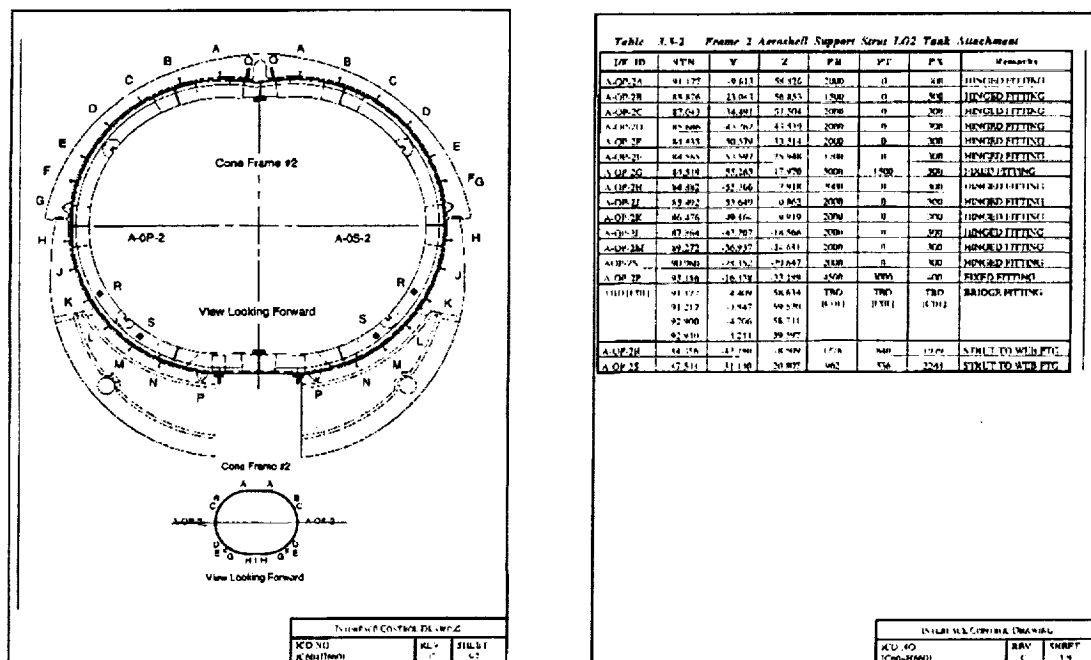


Figure 2. Sample From Lockheed-Martin Michoud's ICD 1

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GRID      302064      85.2022 47.2612 39.7029
GRID      302066      90.3585 14.3892 58.1242
GRID      302075      92.0585 4.3265 59.1155
GRID      302076      92.0585-4.3265 59.1155
$.....1.....2.....3.....4.....5.....6.....7.....8.....9
RBE1      302103      302076 123456 1.0      123456 9002200 9002201
          9002202 9002203
RBE1      302102      302075 123456 1.0      123456 9002206 9002207
          9002208 9002209
$
$INTEG $$ Aeroshell LOX Struts interface grids
GRID      302069      85.1352-56.9733 21.7940
GRID      302070      85.7286-50.3132 42.0806
GRID      302071      91.7596-11.7675 60.4921
GRID      302072      85.1352 56.9733 21.7940
GRID      302073      85.7286 50.3132 42.0806
GRID      302074      91.7596 11.7675 60.4921
$
$INTEG $$ LOX Upper Aeroshell interface grids
GRID      302008      83.4309 61.2794 19.5884
GRID      302009      83.6446 58.3988 28.0126
GRID      302010      84.0784 54.3848 35.8769
GRID      302011      85.1223 46.4254 46.1945
GRID      302012      86.6031 36.3922 54.4952
GRID      302013      88.4963 24.4473 60.6269
GRID      302014      90.8134 10.5549 64.4753
GRID      302016      83.4057 62.3685 14.8052
GRID      302036      83.4309-61.2794 19.5884
GRID      302037      83.6446-58.3988 28.0126
GRID      302038      84.0784-54.3848 35.8769
GRID      302039      85.1223-46.4254 46.1945
GRID      302040      86.6031-36.3922 54.4952
GRID      302041      88.4963-24.4473 60.6269
GRID      302042      90.8134-10.5549 64.4753
GRID      302044      83.4057-62.3685 14.8052
GRID      302056      92.6334-9.37-6 65.6816
GRID      302059      84.7397-50.1385 42.0461
GRID      302061      90.0136-15.2833 63.487
GRID      302065      84.7397 50.1385 42.0461
GRID      302067      90.0136 15.2833 63.487
$
$INTEG $$ WindWard Skin interface grids
$INTEG $GRID      203004      84.9187 59.2187-12.6072
$INTEG $GRID      203005      84.9187-59.2187-12.6072
$
$INTEG $$ WindWard LOXFRM interface grids
$INTEG $GRID      206011      92.5383 24.4025-54.8843
$INTEG $GRID      206012      90.6088 34.4398-50.3431
$INTEG $GRID      206013      88.8647 42.9594-43.4527
$INTEG $GRID      206014      87.2211 50.5423-34.7178
$INTEG $GRID      206015      85.9132 55.9198-24.4057
$INTEG $GRID      206016      84.375 59.8319-.138199
$INTEG $GRID      206017      84.1082 58.4137 14.6675
$INTEG $GRID      206048      94.4133 14.294 -57.5103
$INTEG $GRID      206070      92.5382-24.4025-54.8843
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$INTEG $GRID      206073      87.2218-50.5425-34.7178
$INTEG $GRID      206074      85.9128-55.9197-24.4057
$INTEG $GRID      206075      84.375 -59.8319-.138199
$INTEG $GRID      206076      84.1082-58.4137 14.6675
$INTEG $GRID      206106      94.4133-14.294 -57.5103
$INTEG $
$INTEG $$ LOX Tank interface grids
$INTEG $GRID      9002200      0 91.1770-4.40900 58.6340      0
$INTEG $GRID      9002201      0 91.2170-3.94700 59.5200      0
$INTEG $GRID      9002202      0 92.9000-4.70600 58.7110      0
$INTEG $GRID      9002203      0 92.9400-4.24400 59.5970      0
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$
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$INTEG $GRID      9102225      89.2716 36.9369-24.681
$INTEG $GRID      9102226      90.9599 28.3519-29.6469
$INTEG $GRID      9102227      93.1857 16.438 -33.1889
$INTEG $GRID      9102250      92.2647-21.4419-32.091
$INTEG $GRID      9102251      92.2647 21.4419-32.091

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Majority of model, including grids that do not interface with any other models.

Interface grids to downstream bulkdata files. This is the first time they are defined for the NASTRAN analysis. They are part of this sub model but grouped here for convenience.

Interface grids to upstream bulkdata files. They are commented out to avoid conflict in the NASTRAN analysis. They can easily be uncommented for stand-alone analysis or stand-alone PATRAN database.

Figure 3. Sample of Bottom Portion of a Sub Model Bulkdata File