A2100 COMMERCIAL SATELLITES
INTEGRATED MECHANICAL ANALYSIS

Vince M. Stephens
Staff Mechanical Engineer

Lockheed Martin Missiles & Space
Sunnyvale, California

1997 MSC Aerospace Users Conference
Newport Beach, California
November 17-20, 1997

ABSTRACT

The commercial satellite industry drive towards reducing delivery time requires that mechanical analyses implement production line type methodologies. Analysis of multiple satellites is facilitated by augmenting MSC/NASTRAN with software that automates FEM checkout, sorts multiple load case stresses/forces, prepares reduced coupled loads models, and facilitates pre-environmental test analyses.

INTRODUCTION

MSC/NASTRAN is used as a primary tool for the mechanical analysis of multiple commercial spacecraft designated as the A2100 family of communication satellites. Short order -to-shipdurations have driven the analysis effort to become streamlined and efficient. MSC/NASTRAN is used for satellite and component level static/dynamic analyses, results are input to a suite of proprietary post-processing programs that efficiently automate manipulating and reducing data for presentation, subsequent processing (e.g. internal loads for hand calculations), and environmental testing. Integration of the MSC/NASTRAN finite element model (FEM) and results in an efficient manner with design, analysis, and testing tasks is key towards ensuring mission success and meeting schedules.

Lockheed Martin Missiles & Space (LMMS) Communication Satellite Operations (CSO) designs, integrates, and tests the A2100 commercial satellites. Satellite development was initiated in 1993 by Martin Marietta AstroSpace in East Windsor, NJ. The East Windsor (EW) facility operations are in the final stage of transition to the Lockheed Martin Communications and Power Center (CPC) located in Newtown, PA. The Lockheed Martin organizational structure and key companies that interface with mechanical analysis are shown in Figure 1.

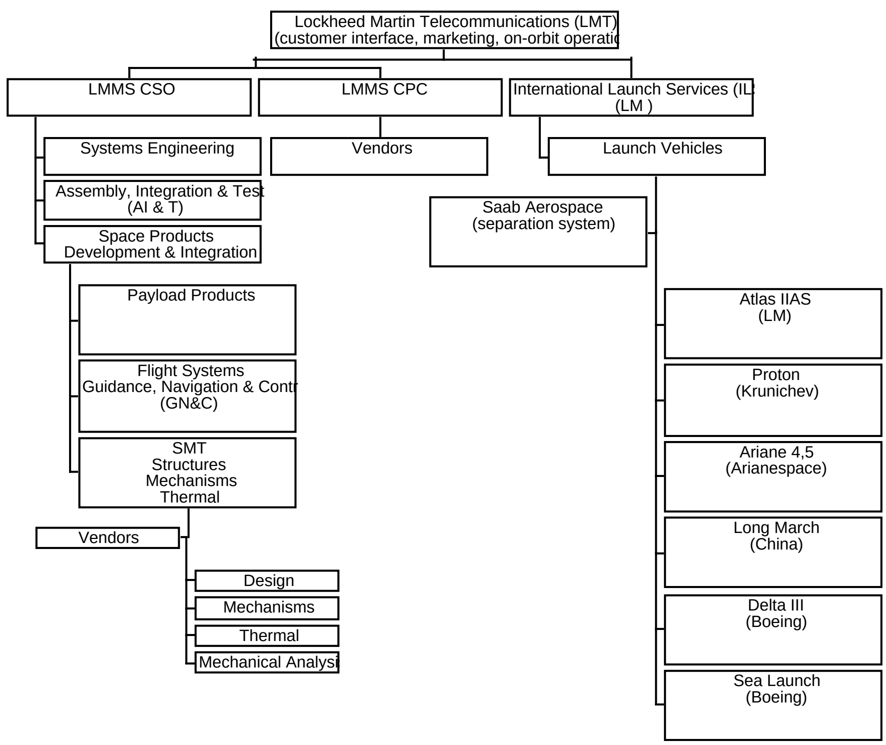

Figure 1
Lockheed Martin Organization - A2100 Commercial Satellites

The A2100 family of satellites consists of “A”, “AX”, and “AXX” satellite buses, each has progressively larger payload capacity. The A2100 satellites provide a low mass/cost structure and modular platform for equipment providing services such as direct broadcast TV, personal mobile cellular communications, etc.

An aggressive bus development program was undertaken by EW to ensure design requirements were met. The EW facility supplied/managed all aspects of design, integration, and test. The responsibilities are now divided, the CPC is responsible for electronic component design, antenna/reflector design, portions of integration, component tests, etc. LMMS SV is responsible for the overall satellite design, integration, and testing.

Currently, a total of eight A2100 satellites are in various phases of completion at LMMS. Echostar III, the first AX bus satellite, was launched by October 5, 1997 aboard an Atlas IIAS launch vehicle (LV). Four other AX, three A, and one AXX vehicles are in various phases of completion utilizing Proton and Ariane as the primary launch vehicles (LV). Four A bus satellites were completed entirely at EW, three are successfully operating (GE-1, 2, 3) and a fourth is awaiting launch (Chinastar-1).

Figure 2 shows a generic schedule from authorization to proceed (ATP, satellite ordered) to delivery. Key milestones such as Preliminary Design Review (PDR), Critical Design Review (CDR) and Coupled Loads Analysis (CLA) model delivery (Preliminary and Final) are shown. Schedule is a key consideration in the development and use of analytical tools.

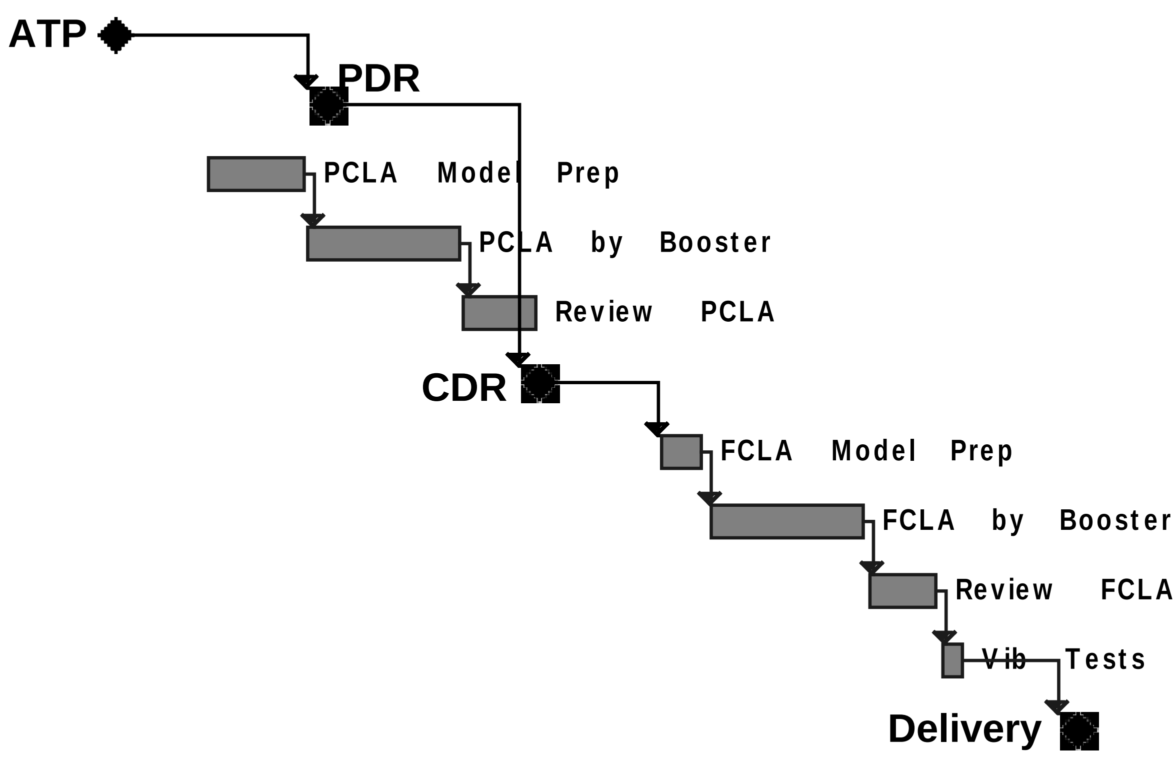

Figure 2
A2100 Satellite Schedule

The A2100 satellite mechanical analysis group provides stress, dynamic, and vibroacoustic analysis capability to support design, integration, and test activities. An overview of satellite design and system requirements is provided herein to highlight the importance of these topics to the analysis effort.

A2100 SATELLITE DESCRIPTION

The A2100 satellite design features a standard core structure supporting the payload panels (transponders and earth) populated with components that reflect the mission specific design. Mission specific earth deck antennas, communication system feeds/horns, and reflectors are also unique to varying degrees for each satellite. Design activities that ensure system requirements are met include spacecraft layout, component packaging, ensuring component on-orbit field of view requirements are met, LV interface requirements, design details, drawing release, etc. Figure 3 illustrates a typical A2100 AX satellite in the stowed for launch configuration, Figure 4 shows the deployed configuration.

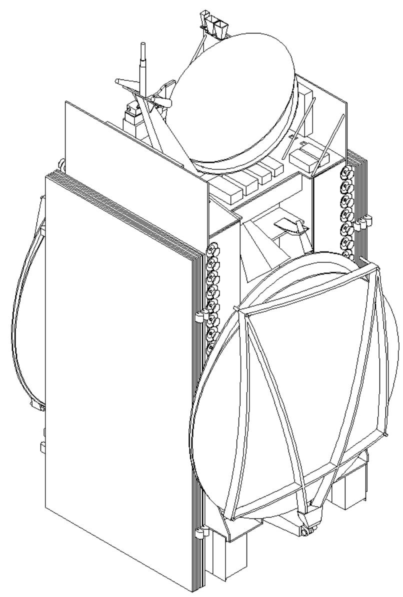

Figure 3
A2100 AX Satellite - Stowed

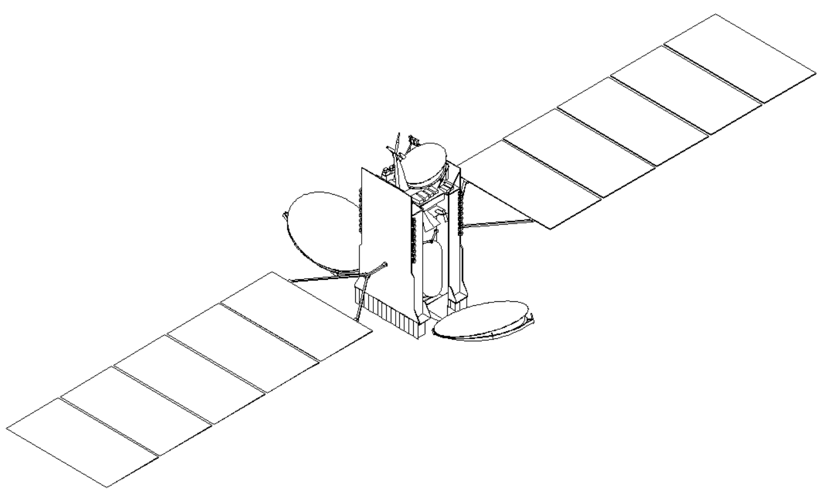

Figure 4
A2100 AX Satellite - Deployed

An exploded view of a stowed A2100 AX satellite indicating key structural and mission components is shown in Figure 5.

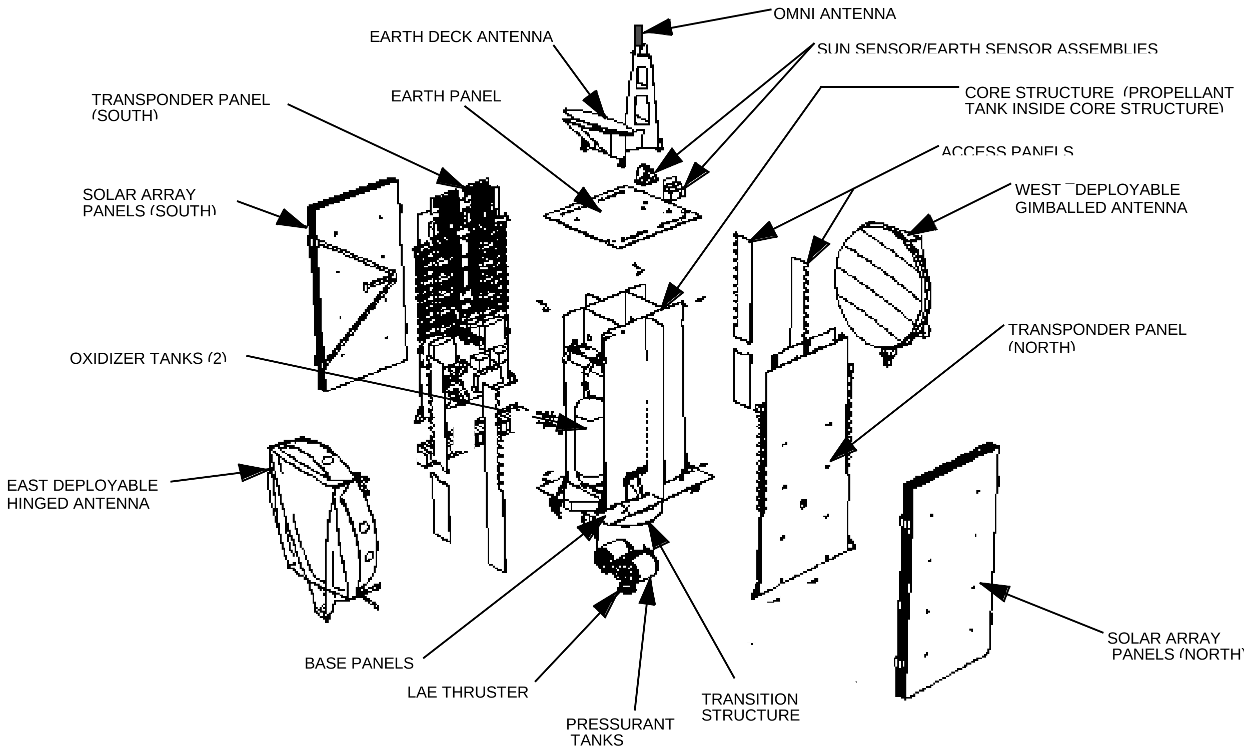

Figure 5
A2100 AX Satellite Design - Exploded View

The primary core structure developed for the A2100 satellites provides a modular design that meets mass and fabrication requirements. The four sided core structure consists of intercostal honeycomb panels with quasi-isotropic graphite/epoxy (Gr/E) facesheets. Facesheet doublers and locally dense core that provides higher insert strengths are incorporated as necessary. The transition structure is a multi-layer Gr/E laminate with Gr/E internal and external stiffeners. This structure transitions from a rectangular box section at the intercostal interface to a circular cross section at the separation ring interface. The transition structure is bonded within a clevis at the top of the separation ring. Three of the intercostals are bonded to each other and the transition structure, the north side is bolted to allow access to the core interior where the single fuel tank is located.

Transponder and earth panels outfitted with components at the CPC are attached to the core structure after the propulsion system is installed. These panels, with embedded heat pipes, have aluminum facesheets for thermal control purposes and contain many equipment inserts bonded within the panel. The base, access, and bridge panels complete the structural system.

A system of structural C (contains nutplate) and Y shaped clips connected by a bolt are used to fasten panel edges. Cup and post bonded close tolerance shear washers are also used for connecting the interior of a panel to another panel edge.

An acceptance level static proof test performed on the core structure ensures the structural integrity and workmanship of the bonded structure.

The primary system/mechanical components of the A2100 satellite are:

Core structure	
N/S & E/W intercostals	Gr/E facesheets, aluminum honeycomb core
Transition structure	Gr/E with internal/external stiffeners
Separation ring	Aluminum, interfaces with LV
Payload Panels (and mounted equipment)	
N/S transponder panels	Aluminum facesheets, core with embedded heat pipes
Earth deck	Same as transponder panel
Base panel	Same as intercostals
Bridge, access, and feed panels	Same as intercostals
CPC structures	
E/W reflectors - gimballed or hinged	
Earth deck antenna - fixed or steerable	
Earth deck tower or tripod structure	
Feeds/Horns	
Electrical Power System	
Solar Array Panels	Kevlar or Gr/E facesheets, honeycomb core
Solar Array boom, shear ties, supports	
Batteries	
Propulsion, GN&C System	
Fuel (hydrazine) and oxidizer (2) tanks	
Liquid Apogee Engine (LAE) tank	
N/S pressurant tanks	
Thrusters, arcjets	
Tubing, valves etc.	
Reaction wheels	
Mechanisms	
Solar array drive, hinges	
Reflector gimbal, hinge	
Pyrotechnic releases (cable cutters)	
Thermal Control System	
Heat pipes	
Heaters	
Surface & reflective coatings	

Major system requirements driving the structural design/analysis are:

- LV User’s Guide stiffness requirements (primary lateral and thrust modes)
- LV User’s Guide quasi-static launch loads (preliminary pending CLA results)
- Component stiffness (avoid coupling with primary modes)
- On-orbit stiffness - solar arrays, reflectors - avoid coupling with GN&C
- Launch mass/cg - contractual limits, mission driven fuel requirements

The extent of mission driven changes from previously designed/analyzed satellite has a major impact on the magnitude of the mechanical analysis effort. The effort is minimized when the new design is popularly called a “clone” - which ideally means very minor changes such as a different reflector surface, different fuel/oxidizer masses, or a different LV. Major new design/analysis efforts using the same bus can occur if dictated by system requirements.

A2100 SATELLITE FEM

The A2100 satellite FEM is constructed using MSC/NASTRAN V69.1 [1] and IDEAS Master Series 4.0 [2] as the primary graphical pre/post processor. The satellite FEM was constructed using a modular approach by specifying the most common interchangeable components via INCLUDE files, thus facilitating analysis of mission specific satellites.

Figure 6 shows an isometric view of an A2100 AX satellite FEM, Figure 7 shows an exploded view.

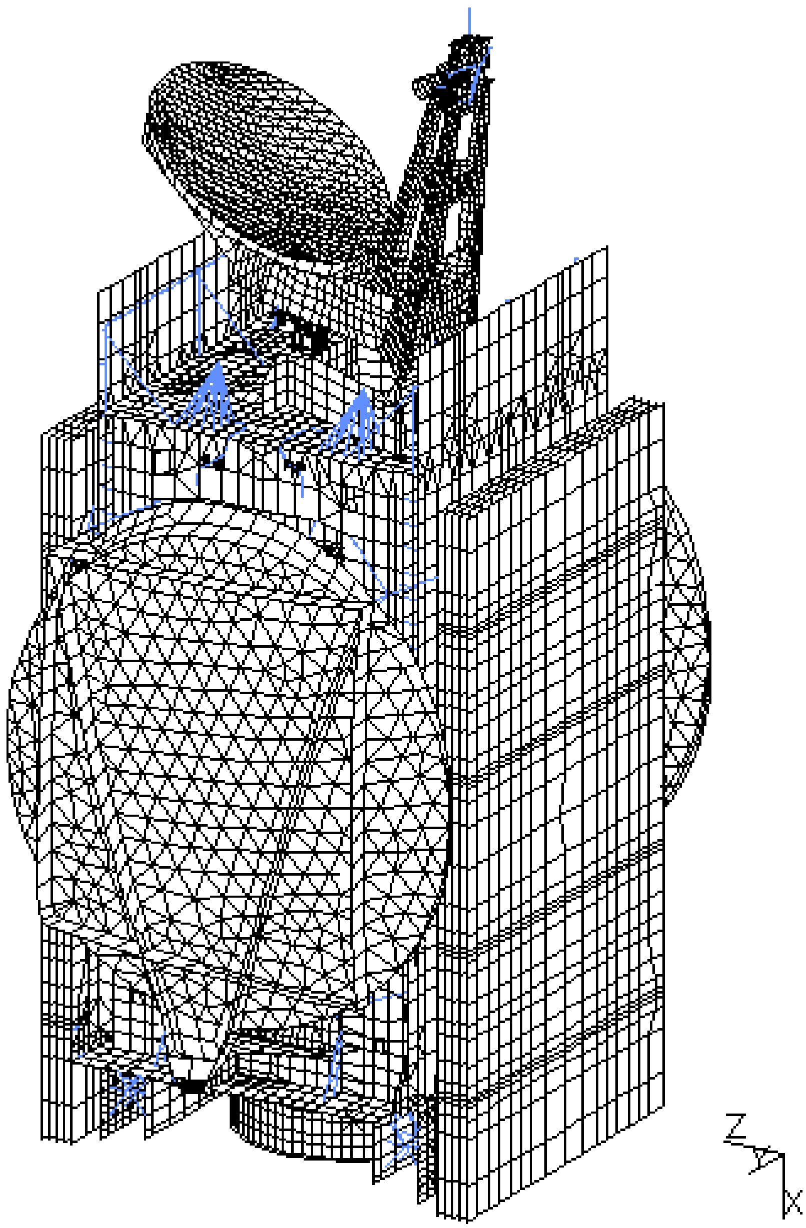

Figure 6
A2100 AX Satellite MSC/NASTRAN FEM

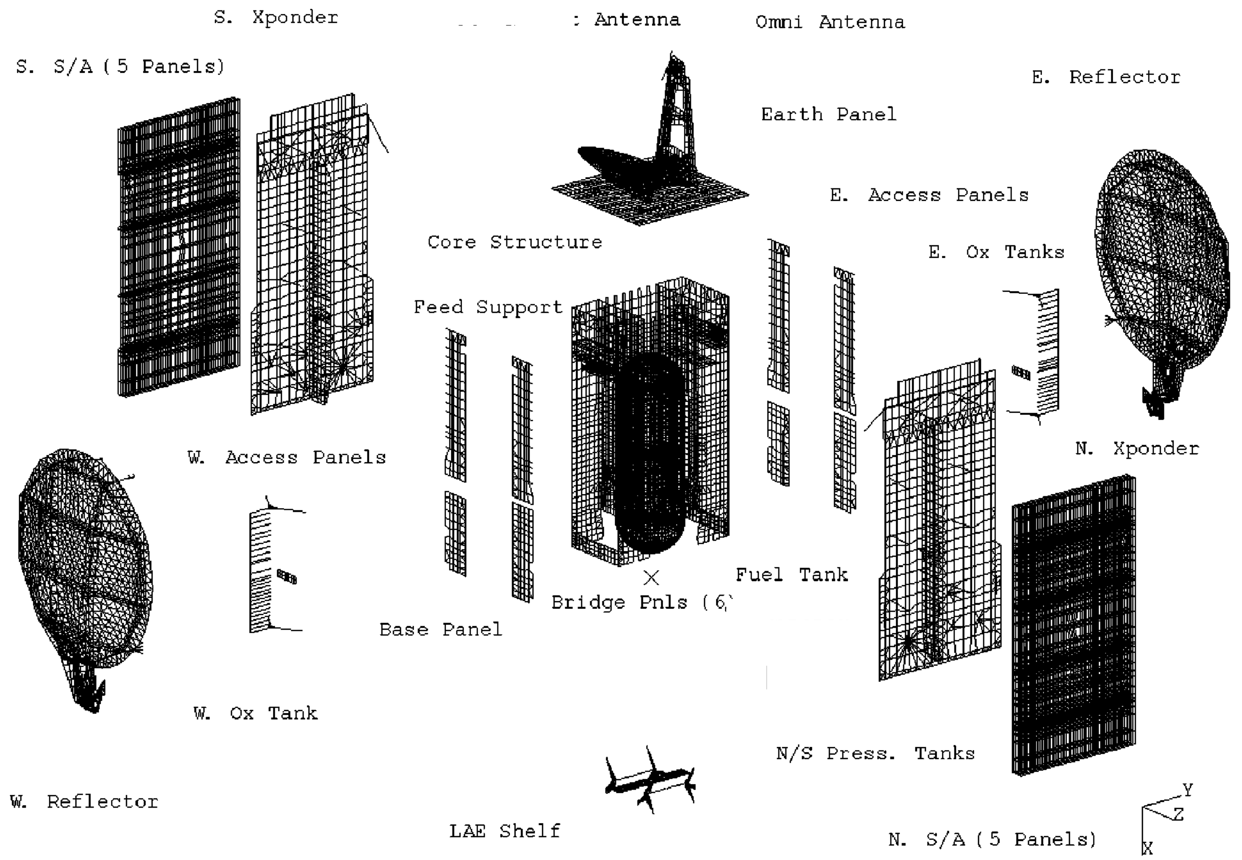

Figure 7
A2100 AX Satellite MSC/NASTRAN FEM - Exploded View

The CPC provides LMMS SV with MSC/NASTRAN FEMs of the E/W reflectors as necessary, as well as the earth deck antennas and feeds/horns. In some cases, earth deck antennas are subcontracted out by the CPC, in this case the CPC acts as an intermediary between LMMS SV and the sub-contractor concerning requirements and analysis results interaction.

FEM Methodology

All A2100 satellite FEMs contain a single grid 6 dof interface to the launch vehicle adapter. This interface is used when determining the reduced FEM Craig-Bampton matrices for CLA.

For the A2100 satellite FEM, the vast majority of elements used are CQUAD4/CTRIA3 with CBAR elements as appropriate. CELASx are used extensively throughout the FEM to specify joint stiffness and extract internal loads. Typically, only translational spring stiffness are specified where a single bolt at a clip or cup/shear washer exists. Significant concentrated masses are represented with a CONM2 and either beamed to the approximate mounting footprint with tuned CBARs or a RBE2/RBE3. The multitude of electrical equipment with many mounting interface bolts is approximated as a uniform NSM over an appropriate area of the payload panels.

Honeycomb panels typically have quasi-isotropic facesheets and are usually modeled with a PSHELL and appropriate MAT1/MAT8 entries. Local doublers may be present, in which case the PSHELL/MAT entry for the facesheet is modified. The option exists to use PCOMP/MAT8 for a layered composite.

For the multi-layer Gr/E transition laminate structure, equivalent PSHELL/MAT8 entries were used by EW to allow use of the post-processors which only handle PSHELL results. As a check, the laminate was constructed layer by layer using PCOMP/MAT8 and using the automatic generation of PSHELL/MAT2 by MSC/NASTRAN. The Gij matrix corresponding to the MAT2 entry was then inverted and the terms corresponding to the MAT8 entry extracted - verification was obtained.

A single satellite MSC/NASTRAN FEM is used for both stress and dynamic analyses. Typically, a dynamic FEM contains significantly less degrees of freedom (dof) than a stress FEM, however the advantages of a single FEM from commonality standpoint outweigh the disadvantages of increased computer memory, processing time, and results storage disk space. No static/dynamic reduction or DMIG representation of components is needed. Typical run times for a 170,000 dof AX satellite FEM on a SGI Power Challenge R8000 are 37 minutes for a V69.1 SOL 101 with 131 subcases and 172 minutes for a V68.2 SOL 3 extracting 241 flexible modes up to 75 Hz.

FEM file control is essential when dealing with multiple satellites and numerous INCLUDE commands that read in separate files to assemble a satellite FEM. Controlled location of baseline FEM files must be established and maintained, unnecessary duplication of INCLUDE files by individuals is to be avoided.

Post-Processor Interfaces

While executing and obtaining results from MSC/NASTRAN is a cornerstone of the analysis effort, it is only a portion of the total task. Extensive post-processing and data reduction is required to digest and present the results. A collection of custom post-processing programs were initiated at EW to facilitate processing of MSC/NASTRAN results. These programs, with input requirements, output, and sample file listings, are described in a user’s manual [3].

Pre-solution FEM data in an orderly form is supplied by *femass*, it also formats files to be used as input for other post-processors. Mass properties are listed with respect to PID, providing useful component mass information. In addition, available gaps in the FEM grid number/EID, CELAS non-zero lengths or inconsistent coordinate systems, rigid element listings, and duplicate EIDs are listed.

For static solutions, several programs are available that read the OUTPUT2 file and sort results and/or compute margins of safety (MS) values. No special DMAP alters or PARAM entries are required. Some of the LV User’s Guide (e.g. Proton) lateral loads are specified as linearly varying magnitude from the spacecraft/LV interface to the top of the spacecraft primary structure. These linear varying and stand alone component quasi-static g loads cannot be specified with a uniform g load (GRAV) applied to the entire satellite FEM. *new-mforce* is used to generate these loads as well as subsystem loads.

Dynamics post-processors are used as a substitute for the SOL 30 (unstructured) solution sequence and still provide the same capability as those for statics. A V69.1 DMAP alter which slightly modifies the standard SOL 103 alter available from MSC supplies rigid body checks, etc.

CLA model processing uses a V68.2 alter (latest available). The CLA alter provides Craig-Bampton matrices formatted as required for the LV contractors. Additional standardized SOL 100 generic files are available for conversion to metric units and to generate a modal damping matrix. *bdrive* provides a method to compute dynamic responses in lieu of the long turnaround CLA cycle. A best available, same LV, interface time history is used to excite the Craig-Bampton model of the satellite and calculate the same response types/locations as obtained for a CLA.

A2100 MECHANICAL ANALYSIS

Mechanical Analysis Tasks

A consistent, streamlined, and efficient mechanical analysis effort is required when analyzing multiple satellites in various stages of design, fabrication, and test. System requirements must be flowed down from the appropriate sources. Interaction between design, other disciplines and analysts is essential. Mechanical analysis design criteria, composite allowables, etc. must be clearly defined. Cognizance and resolution of these issues facilitates the analysis effort. Figure 8 illustrates the major tasks, those tasks related to key analyses/reports are shaded.

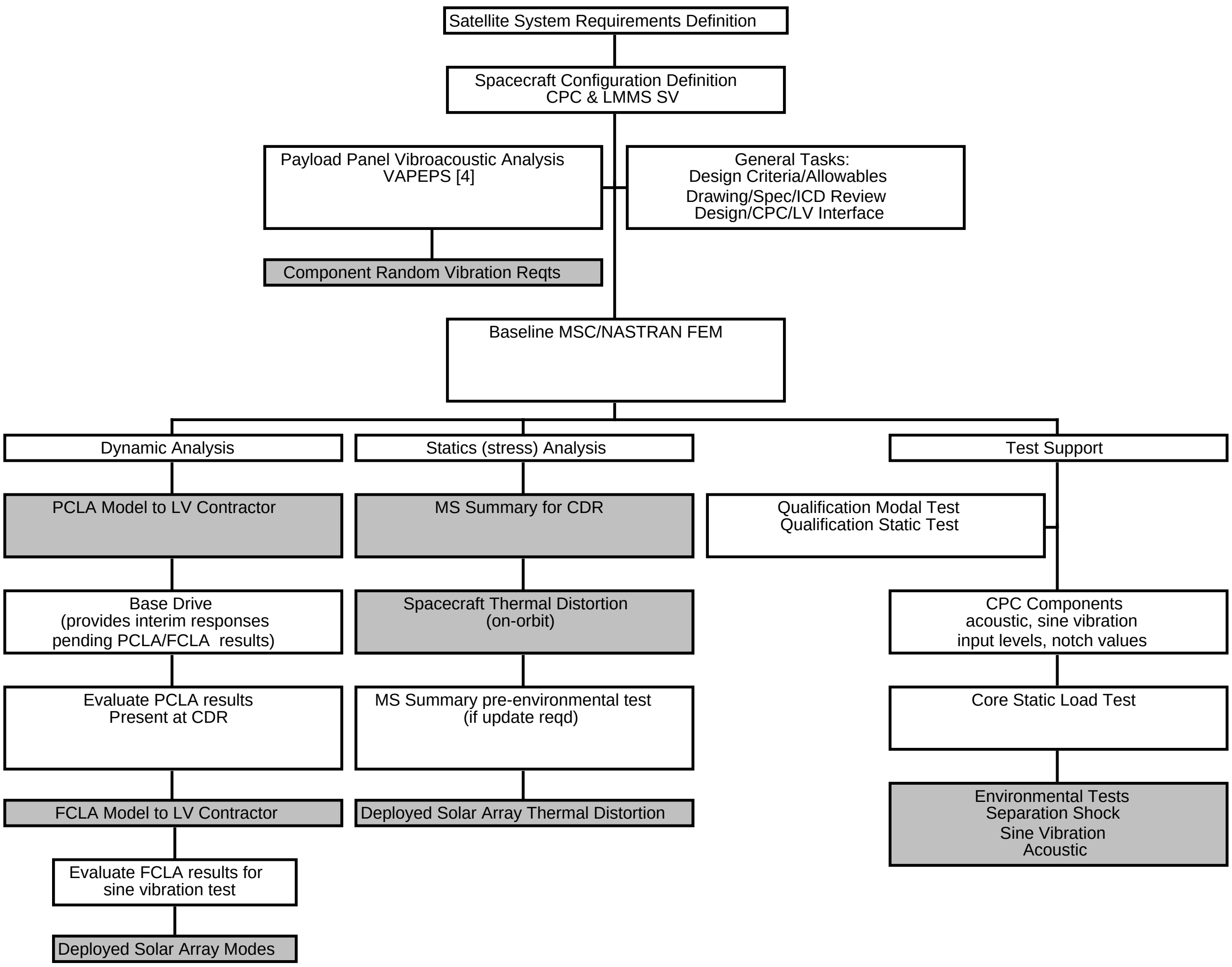

Figure 8
A2100 Satellite Mechanical Analysis Tasks

Linear Statics Post-Processors

The automated linear statics analysis flow is based on a satellite level FEM containing all required subcases. These subcases consist of:

- Launch Vehicle User's Guide quasi-static loads for launch events
- Honeycomb panel and component normal quasi-static loads - quasi-static equivalent of acoustic loads
- Subsystem quasi-static equivalent of coupled loads responses - single or 3 axis combinations
- On-orbit thermal loads to compute spacecraft thermal distortion - part of pointing error budget

Figure 9 depicts the linear statics post-processor programs.

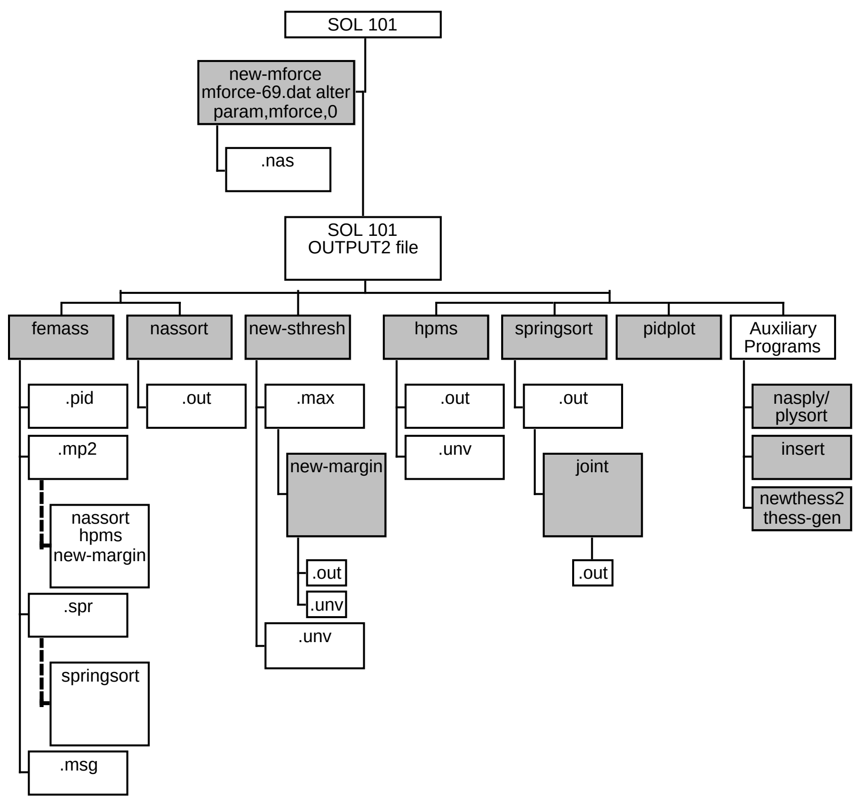

Figure 9
Linear Statics Post-Processors

femass	Mass properties by PID, available FEM gaps, CELAS listing, input files for other programs
hpms	Calculates honeycomb facesheet/core MS using Bruhn [5] (use for aluminum facesheets)
insert	Insert allowables/MS using CELASx forces
joint	Aligns grid numbers, CELASx EID along joint line, use with springsort
nassort	Sort results for all static load subcases - max/min stress/force/displacement
nasply/plysort	Reads PCOMP produced data, performs ply by ply analysis
new-margin	Calculates honeycomb facesheet/core MS using MIL-HDBK-23 (use for Gr/E facesheets)
new-mforce	Creates FORCE/MOMENT entries based on user supplied acceleration profile
new-sthresh	Creates max force/stress envelope for plate elements using PSHELL
pidplot	Alternative to IDEAS, plots geometry/results, postscript compatible
springsort	Prints max/min forces for groups of CELASx
newthess2	Converts SINDA thermal analysis model/results to MSC/NASTRAN TEMPxx entries

Dynamics Post-Processors

The dynamics analysis post-processors were developed in order to (1) automate the process of producing Craig-Bampton CLA models, (2) provide sorting/MS results similar to the statics processors, and (3) after MSC/NASTRAN is used to obtain modes, allow subsequent analyses in a simplified form as a substitute for MSC/NASTRAN SOL 30.

The V69 structured SOL 103 alter is available for the modal solution, however only V68.2 alters are available for the CLA generation and other auxiliary programs. Figure 10 shows the post-processors.

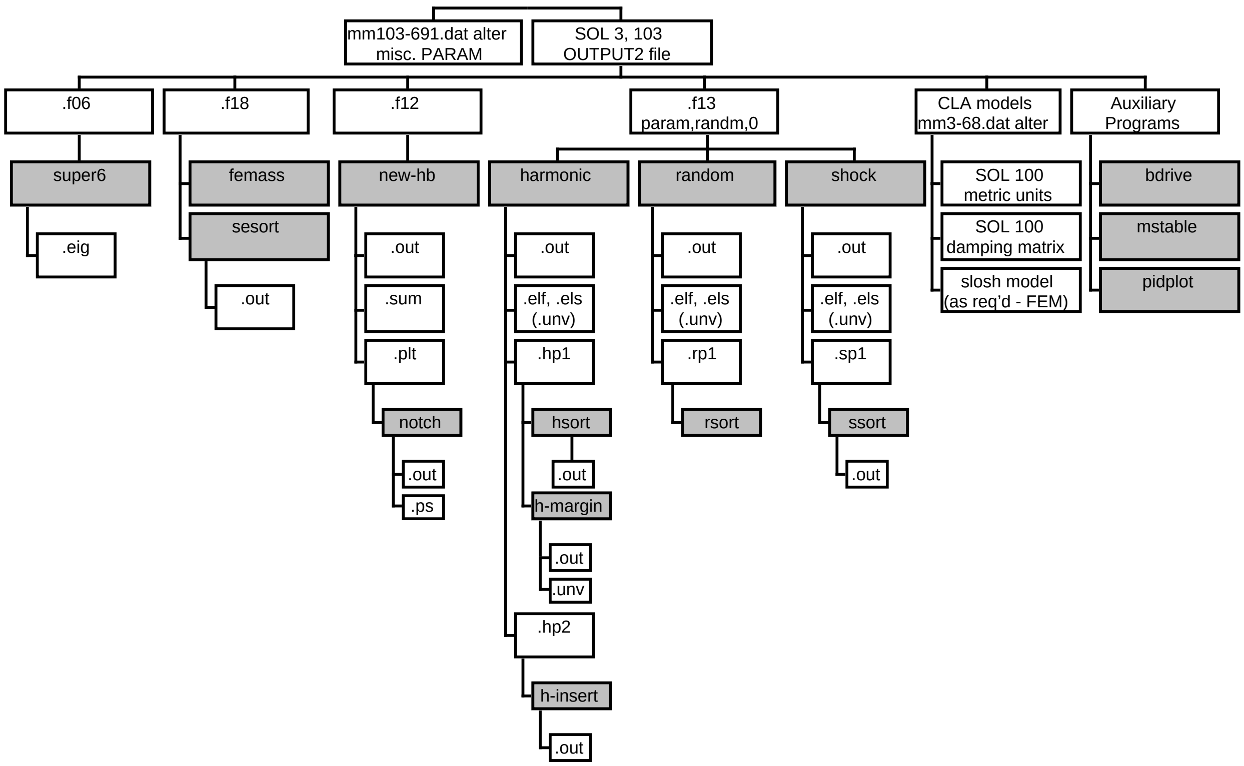

Figure 10
Dynamic Analysis Post-Processors

bdrive	Computes responses for Craig-Bampton input model using time history forcing function
harmonic	Calculates force/stress response for base harmonic (sinusoidal) input. Substitute for SOL 30
h-insert	Equivalent of insert for harmonic loads
hsort	Sorts results from harmonic
h-margin	Calculates/sorts honeycomb panel MS for base harmonic (sinusoidal) excitation
mstable	Formats modal analysis results for GN&C use (deployed solar arrays)
new-hb	Calculates acc/disp for base harmonic (sinusoidal) or random input. Substitute for SOL 30
notch	Computes notched input motion based on user specified limits
random	Calculates force/stress responses for base random input. Substitute for SOL 30
rsort	Sorts results from random
shock	Calculates force/stress responses for base response spectrum input. Substitute for SOL 30
sesort	Sorts element strain energy by PID and EID
ssort	Sorts results from shock
super6	Eigenvalue summary, modal weights

Environmental Testing

Environmental tests at the spacecraft level requiring mechanical analysis are shock (separation system clamp band, deployable reflector and solar arrays), sine vibration, and acoustic. The sine vibration test will be discussed as it relates to use of post-processing programs that interface with MSC/NASTRAN.

Nodal acceleration/displacement responses using modes obtained from MSC/NASTRAN and a generic sine vibration input specified per the LV User's Guide are calculated using *new-hb*. The satellite is in the stowed configuration except that tanks are dry and pressurized to specified levels. The satellite is mounted to a test equipment adapter with a flight-like clamp band, the adapter is then attached to the shake table. The test configuration is reflected in the FEM.

Program requirements dictate that the sine vibration test induce a base bending moment that envelopes the FCLA prediction times a factor (usually 1.25). In addition, component loads are not to exceed 80% of the design (ultimate) loads. The LV sine vibration environment requires notching to achieve these requirements. These requirements are specified as input to *notch* and the input profile is then calculated for the pre-test prediction.

A representative pre-test notched input profile for an AX satellite is shown in Figure 11. The notched profile is used as a guide for the actual sine vibration test. The final notched input is determined during the sine vibration test based on the measured responses via accelerometers at pre-determined locations. Accelerometers with abort limits whose response is monitored by the shake table control system provides automatic shutdown capability to prevent overloading components.

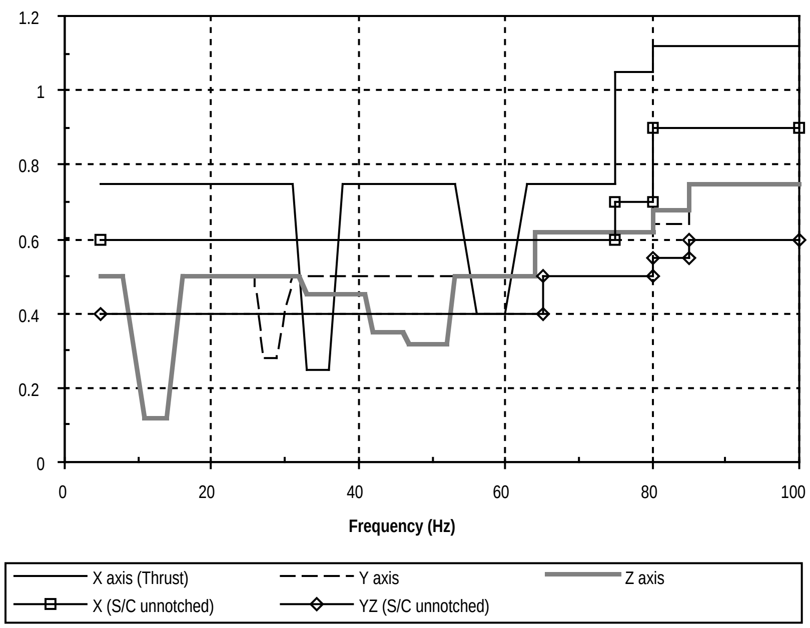

Figure 11
A2100 AX Notched Sine Vibration Input

CONCLUSIONS

Integrated mechanical analysis of multiple commercial satellites is predicated on using MSC/NASTRAN as the FEM foundation. System and design requirements also drive the analysis. Identification of major analysis tasks and proprietary MSC/NASTRAN interface post-processors provide an analysis flow that aids in completing required tasks to meet aggressive schedules. The post-processors allow efficient evaluation of simultaneous commercial satellites throughout the design, analysis, and test phases.

MSC/NASTRAN provides a wealth of analysis raw results. However, obtaining raw results is only a portion of the total analysis effort required. Lack of MSC supplied numerical post-processors led to the development of the suite of post-processors that allow concise summary of loads/MS without resorting to third party graphical software such as IDEAS, which is not proficient at handling many load cases. Development and maintenance of the post-processors is time consuming and requires personnel adept in not only coding but also DMAP and analysis experience (in order to format/assess the programs). MSC is better suited to author/maintain software than aerospace companies with non-software priorities and analysts who concentrate on being end users of software. The aerospace user community would be best served by MSC making available a set of dedicated post-processors that are standardized, with proper quality assurance, and updated as required for new releases and capabilities of MSC/NASTRAN.

ACKNOWLEDGMENTS

The author expresses his appreciation for the development, verification, and documentation of the MSC/NASTRAN post-processing suite of software originated by a multitude of people at the East Windsor, NJ and Valley Forge, PA facilities. This software was invaluable in aiding the transition of the A2100 satellite mechanical analysis effort to LMMS. In particular, Mohan Barbela provided unique insight into the structure and use of the programs and also transferred and updated the software to the LMMS computer system. In addition, Larry Loh and other LMMS personnel provided valuable peer review of this paper.

REFERENCES

[1] *MSC/NASTRAN Quick Reference Guide, Version 69*, The MacNeal-Schwendler Corporation, Los Angeles, October 1996.

[2] *I-DEAS FEM User’s Guide, Volumes I and II P-40044A/B, Master Series 4*, Structural Dynamics Research Corporation, 8/96.

[3] *Mechanical Analysis Software*, Mohan Barbela, Lockheed Martin Missiles & Space AstroSpace, East Windsor, NJ.

[4] VAPEPS (Vibro Acoustic Payload Environment Prediction System) User’s Reference Manual, Version 5.0, Lockheed Missiles and Space Company, July 1988.

[5] Analysis and Design of Flight Vehicle Structures”, E.F. Bruhn, Jacobs Publishing, 1973.