Full Vehicle Dynamic Analysis using Automated Component Modal Synthesis

Peter Schartz, Parallel Project Manager
ClusterWorld Conference
June 2003
Full Vehicle Dynamic Analysis

- Noise, Vibration, and Harshness (NVH)
  - “Roadnoise”
- Important Items:
  - Acoustic level at your ear
  - Acceleration at your seat
  - Steering wheel shake
  - From engine idle to high RPM
- Fatigue / durability
- Competition
MSC.Nastran

- General purpose finite element analysis program
- Originated with NASA (1970s)
- Extensive worldwide use
  - Automotive
  - Aircraft / Spacecraft
  - Manufacturing
Frequency Response Analysis

- Steady-state oscillatory excitation
- Excitation defined explicitly in frequency domain
- Applied forces are known
- Unknowns include displacement, velocity, acceleration
Two Approaches: Direct and Modal

- **Direct:**
  - Complex solution at each discrete frequency
  - Physical domain

- **Modal:**
  - Eigenvectors (mode shapes) instead of physical variables
  - Transform from physical to modal coordinates, and back
  - Approximation when Nmodes $<<$ Ndof
  - Natural extension of normal modes
  - Ease of “modal damping” input
  - Less expensive
Dynamic Equation – General Form

\[
\begin{align*}
[M_{xx}]\{\ddot{u}_x\} + [B_{xx}]\{\dot{u}_x\} + [K_{xx}]\{u_x\} &= \{P_x\} \\
\{\ddot{u}_x\} &= \left\{ \frac{du}{dt} \right\} \text{ is the vector of grid point velocities.} \\
\{\dddot{u}_x\} &= \left\{ \frac{d^2u}{dt^2} \right\} \text{ is the vector of grid point accelerations.}
\end{align*}
\]

where \( \{u_x\} \) is the vector of grid point displacements.

\( x \) = Number of (Active) physical DOF (direct), or Number of generalized coordinates (mode shapes)
If $N_{dof} \gg N_{modes}$, modal approach is more efficient

Computing the eigensolution becomes primary computational concern

Conflicting goals: analysis time vs. accuracy
  - Modal truncation
  - Accepted level of accuracy
Industrial Trends

Early-mid 1990s
- Low frequency, structure-only
- Increasing model size, complexity (up to 1M DOF)
- Sparse matrix methods
- Vector supercomputer hardware

Mid-late 1990s
- Mid frequency, structure plus fluid (acoustics)
- Two and three million DOF
- Cache based RISC, commodity components
Industrial Trends (continued)

- **Current**
  - High frequency, structure plus fluid (acoustics)
  - Model sizes (up to one million grid points)
  - Dense matrix methods
  - Inexpensive hardware

- **Future**
  - Higher frequency
  - Model sizes increasing
  - Inexpensive network clusters
Limitations to Modal Approach

- Global eigensolution
  - Block-shifted Lanczos algorithm (Boeing)
  - Vector supercomputer hardware paradigm
  - Large disk I/O cost

- Modal density increases with frequency range

- Past: Less than one million DOF, 500 modes
  - Overnight turnaround

- Present: More than one million DOF, 1000 modes
  - Two days or more
Modified Modal Approach

- High level domain decomposition
- Component modal reduction
- Global eigensolution is replaced by an approximation
- MSC.Nastran Automated Component Modal Synthesis (ACMS)
Dynamic Equation – Reduction Form

\[
\begin{bmatrix}
M_{aa} & M_{ao} \\
M_{oa} & M_{oo}
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_a \\
\ddot{u}_o
\end{bmatrix}
+ \begin{bmatrix}
B_{aa} & B_{ao} \\
B_{oa} & B_{oo}
\end{bmatrix}
\begin{bmatrix}
\dot{u}_a \\
\dot{u}_o
\end{bmatrix}
+ \begin{bmatrix}
K_{aa} & K_{ao} \\
K_{oa} & K_{oo}
\end{bmatrix}
\begin{bmatrix}
u_a \\
u_o
\end{bmatrix}
= \begin{bmatrix}
P_a \\
P_o
\end{bmatrix}
\]

where:

▲ a is the analysis set, to be retained: boundary points
▲ o is the omitted set, to be eliminated: interior points
Component Modal Synthesis

- Stiffness is exact
- Mass and damping reduction are approximate
- Independent DOF are represented by their mode shapes
  - Fixed boundary points used to solve for interior
  - Craig-Bampton method
  - [http://analyst.gsfc.nasa.gov/FEMCI/craig_bampton](http://analyst.gsfc.nasa.gov/FEMCI/craig_bampton)
    - Scott Gordon, NASA Goddard
What is ACMS?

- Automated Component Modal Synthesis (ACMS) combines domain decomposition with component modal synthesis.
- The model is divided into N domains (components) automatically via nested dissection.
  - Binary tree is formed
- Component modal reduction
  - Craig-Bampton (fixed boundary points)
- Residual vector augmentation at each component
- Parallel ACMS (PACMS) is the execution of ACMS on multiple processors in parallel.
Binary multilevel tree
Static domain assignment

Binary multilevel tree - NDOM=16, DMP=4

- Master 29
- Slave 1 26
- Slave 2 27
- Slave 3 30

June 2003  ClusterWorld
ACMS Performance Advantage

- Modal reduction results in fewer operations
- No single large eigensolution
  - Disk I/O cost
- Smaller order of calculations
  - Tens of thousands vs. millions
  - More advantageous for cache based processors
- Two- or Three-to-One Speedup is Typical
- Parallel ACMS Increases Job Turnaround
  - Additional speedup
ACMS vs. Standard Modal Approach

- Advantage for Problems with High Modal Density

**General ACMS Performance Trend**

- **Time**
- **No. of Eigenvalues**

- Blue line: Standard Modal
- Pink line: ACMS
ACMS Benchmarks

- Itanium2 cluster running Linux
- Two Automotive Models
- Resource Utilization
  - CPU and Elapsed Time
  - Disk Space and Memory Requirements
  - Disk I/O Transfer Requirement
- Results Comparison
Cluster Configuration

Node: QUAD1
HW: HP ZX1
OS: MSC.Linux
CPU: Itanium2 (2)
Mem: 12Gb
Disk: 66Gb

Node: QUAD0
HW: HP ZX1
OS: MSC.Linux
CPU: Itanium2 (2)
Mem: 4Gb
Disk: 66Gb

Node: IA64
HW: Intel Tiger
OS: Redhat
CPU: Itanium2 (4)
Mem: 4Gb
Disk: 70Gb

Node: ALTIX
HW: SGI Altix
OS: Redhat
CPU: Itanium2 (4)
Mem: 8Gb
Disk: 63Gb

ClusterWorld

[Gigabit Ethernet connection]
Case Study 1 – GM model

- Acoustic “idle shake”
- 312,000 grid points (1.8 million degrees of freedom)
- 500 modes up to 150 Hz
- 160 forcing frequencies up to 80 Hz
- Two load cases
Case Study 1 – GM model
Case Study 1 – Performance Data

Serial Performance

Parallel Performance

Minutes

ACMS-1
ACMS-2
ACMS-4

June 2003
ClusterWorld
Case Study 1 – Disk Space Utilization

Maximum Disk Space - Serial

- 1-Shot: 25 GB
- ACMS-1: 0 GB

Maximum Disk Space per Parallel Process

- ACMS-1: 7 GB
- ACMS-2: 3 GB
- ACMS-4: 2 GB
Case Study 1 – Disk Input/Output

Total I/O - Serial

Max Total I/O per Parallel Process

June 2003

ClusterWorld
Case Study 2 – Opel model

- Acoustic analysis
- 1.3 million grid points (7.9 million DOF)
- 1000 modes up to 300 Hz
- 190 forcing frequencies
- 21 load cases
Case Study 2 – Opel model (example)
Case Study 2 – Performance Data

Serial Performance

Parallel Performance

Hours

0
20
40
60
80
100
120
140
160

Hours

0
5
10
15
20
25

Elap
CPU

ACMS-1
ACMS-2
ACMS-4

June 2003

ClusterWorld
Case Study 2 – Disk Space Utilization

Maximum Disk Space - Serial

Maximum Disk Space per Parallel Process

June 2003
Case Study 2 – Disk Input/Output

Total I/O - Serial

Max Total I/O per Parallel Process

GB

June 2003

ClusterWorld
Case Study 2 - Sample Results

Subcase 1 Grid 1000157

Frequency (Hz)

Accel (t3)

1shot

acms
Case Study 2 – Sample Results (cont)

Subcase 2 Grid 1000157

Accel (t3)

Frequency

1shot
acms
Case Study 2 – Sample Results (cont)

Subcase 3 Grid 1000157

Accel (t3)

Frequency

1shot
acms
Subcase 2 Grid 1000167

Accel (t3) vs. Frequency

-40.000 -30.000 -20.000 -10.000 0.000 10.000 20.000 30.000 40.000 50.000 60.000

0.0 25.0 50.0 75.0 100.0 125.0 150.0 175.0 200.0

1shot
acms
Case Study 2 – Sample Results (cont)

Subcase 3 Grid 1000167

Frequency

Accel (t3)

1shot
acms
Conclusions

- ACMS technology is essential to meet current automotive dynamic analysis needs
  - Overnight job turnaround on inexpensive platforms
  - Minimum resource usage
  - Excellent accuracy
- Parallel ACMS Useful for Increased Performance
- Further adaptation required as trends continue