Efficient Modeling of Vehicle NVH from Low- to Mid- to High-Frequency Ranges

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Overview

■ Current ARC research in structures and dynamics

■ Noise and vibration sources
  ◆ Ground vehicles
  ◆ Tracked vehicles

■ Low- to mid-frequency vibration and power flow

■ Radiated noise and acoustic signature

■ High-frequency vibration
ARC Thrust Area: High Performance Structures and Materials

- Develop efficient models and analysis techniques for vehicle structures and materials to promote high-fidelity simulation
  - Dynamics, vibrations, and acoustics
  - Durability and fatigue life

- Develop and implement design optimization methodologies
  - New materials and components
  - Multiple objectives for performance and durability
Key Research Issues

- Efficient modeling techniques for vehicle dynamics, vibration, radiated noise, and acoustic signature
- Predictions of NVH across a wide frequency range
- New simulation and modeling tools to enable durability analyses and design
- Integration of models in a distributed, flexible design environment
  - New, modular framework for global analysis
- Analysis capabilities for emerging class of light-weight vehicle body structures (e.g., hybrid vehicles)
  - Likely to suffer from vibration problems
  - More likely to have “mid-frequency” vibration
Simulation and Modeling

- External acoustic field model
- Track/wheel/terrain interaction model
- Track/sprocket contact model
- Acoustic model
- Power Flow Model
- Mid-frequency analysis model
- Optimal material model
- Engine model
- Material design model
- Fatigue life prediction model
- Track/wheel/terrain interaction model
- External acoustic field model
- Track/wheel/terrain interaction model
- Track/sprocket contact model
- Acoustic model
- Power Flow Model
- Mid-frequency analysis model
- Optimal material model
- Engine model
- Material design model
- Fatigue life prediction model
New Case Studies

- Body structure of military vehicle
  - Structural Dynamics
  - Radiated Noise

- Hybrid Truck
  - All projects
Application and Integration of Models

Sources of Vibration and Noise

High-Frequency: Energy FEA

Low-Frequency to Mid-Frequency: FEA and Reduced Order Modeling

Radiated Noise Prediction

Thrusts 1 and 3
Vehicle Dynamics Simulation

Thrust 4
Powertrain Simulation
Predicting Sources of Vibration and Noise

Needs for tracked vehicles:
- Protect on-board instruments and personnel from shock and vibration
- Improve personnel performance
- Reduce vibration, noise, and fatigue
- Predict acoustic and seismic signatures
Major Sources of Vibration, Noise, and Seismic Force for Tracked Vehicles

- Track vibration due to:
  - inertia loading
  - dynamic tension
  - contact/impact with support rollers
- Track/sprocket contact and impact
- Track/wheel/terrain interaction
- Powertrain dynamics
Subsystem Models For Predicting Sources of Vibration, Noise, and Seismic Force

- External acoustic field model
- Track/vibration model
- Acoustic model
- Vehicle model
- Track/sprocket contact model
- Engine model
- Track/wheel/terrain interaction model
Vehicle Dynamics Simulation

Terrain: TACOM profile 4

Time history

Frequency response
FEM of the Vehicle Body Structure

Finite Element Model (1000Hz Model)
- Max size of mesh = 2.0 in
- 20,000 plate elements
- 115,000 DOF
- 27 modes under 100 Hz
- 1,043 modes under 1,000 Hz

Modal Density

Rear View

Loads predicted from the previous dynamic simulation

Mode 1 (21.52 Hz)

Node 19194

Mode 20 (81.62 Hz)
Predicted Response of the Body Structure

**Total input power**

- Peak response at 28.1 Hz
- Peak response at 111.1 Hz

Frequency (Hz)

Total Input Power of the System

Power Density

- 28.1 Hz
- 53.7 Hz
- 111.1 Hz

Predicted Response of the Body Structure

- 53.7 Hz
- 28.1 Hz
- 111.1 Hz
Effect of Design Changes on the Structural Response

$K_T$ - Track Stiffness
$K_B$ - Torsion Bar Stiffness
$C_B$ - Torsion Bar Damping

Variation 1
$K_T = 0.5 \times \text{baseline}$
$K_B = 0.5 \times \text{baseline}$
$C_B = \text{baseline}$

Variation 2
$K_T = 0.5 \times \text{baseline}$
$K_B = 0.5 \times \text{baseline}$
$C_B = 2 \times \text{baseline}$

Baseline

Variation 1

Variation 2
Summary: Modeling NVH Sources

- Modeling and simulation tools have been developed for predicting various sources of vibration and noise

- Flexible simulation environment has been established
  - Subsystem models may be chosen for desired fidelity and efficiency
  - Capabilities may be used for designing new concept vehicles

- Simulation results provide input for structural dynamics and durability analyses
Efficient Modeling of Low- to Mid-Frequency Vibration and Power Flow

- Component structure approach
  - Reduces FEA costs
  - Provides ideal framework for power flow analysis
  - Allows modification and re-design of individual components
  - Offers distributed design simulation

- Reduced order modeling
  - Find component modes via FEA
  - Capture primary interface motion with “characteristic constraint modes”
  - Construct low-DOF models in frequency range of interest
CC Modes: Primary Interface Motion

Illustrative Example: Cantilever Plate

First Six CC Modes (Plate 2 Shown)
CC Mode 2 and Natural Frequencies for Vehicle Body Structure (Coarse Mesh)
Power Flow Results (Coarse Mesh)
Multi-Level Substructuring Technique

1. Split component structure FEMs into sub-component FEMs
2. Perform FEA on sub-components
3. Use sub-component modes to find component modes and CC modes
4. Calculate global modes, vibration, and power flow
Natural Frequency Results (Fine Mesh)

Comparison of Lowest 385 Natural Frequencies

- 61 cc-mode model (516 DOF)
- 194 cc-mode model (649 DOF)
- FEM (115,344 DOF)

% error

- 61 cc-mode model
- 194 cc-mode model
Forced Response Results (Fine Mesh)

Node 19194

Power Flow: ROM (516 DOF)

Comparison of displacement at node 19194

Displacement at Node 19194:
FEM (115,344 DOF) vs. ROM (516 DOF)
Power Flow Results (Fine Mesh)

**Baseline**

**Variation 1**

**Variation 2**
Summary: Low- to Mid-Frequency Vibration and Power Flow

- New modeling techniques allow efficient analysis of vibration and power flow
  - Fast yet accurate for low-frequency range
  - Suitable for mid-frequency range

- Multi-level substructuring approach provides new capabilities for analysis and design
  - Analysis of extremely large FEMs
  - Use of “library” of sub-components: plates, beams,...

- Framework has been established for distributed design simulation
  - “Test” and modify individual components
  - Optimize design of global structure
    - Supports target cascading approach
Boundary Element Models for Predicting Radiated Noise and Acoustic Signatures

- FEM: Structural Vibration
- BEM: Radiated Noise
  - Passenger compartment noise
  - Drive-by noise
  - Acoustic signature
Vibro-Acoustic Response

Structural Vibration

Radiated Noise

Acoustic Intensity
Acoustic Pressure, 28 Hz

Baseline

Variation 1

Variation 2
Summary: BEMs for Radiated Noise

- Radiated noise can be predicted by integrating:
  - Vehicle dynamics simulation
  - Structural vibration analysis
  - Acoustic radiation analysis

- Acoustic analysis is needed to determine best/worst design cases
  - Acoustic radiation efficiency plays important role
  - Noise levels may not correlate with vibration levels
    - “Variation 1” is best case for noise
    - “Variation 2” is best case for vibration

- Technique can be used for both exterior and interior (passenger compartment) noise predictions
Energy Finite Element Analysis for High-Frequency NVH

Conventional FEA Model
Primary Variable: Displacement

Energy FEA Model
Primary Variable: Energy Density

Both models generated from same geometry data

Fewer elements, yet well-suited for high-frequency analysis
Energy Ratio Between Various Vehicle Locations and Input Location (Side)

![Energy Ratio Graph]

- Top
- Back
- Front
- Side
- Bottom

Location of input power
Flexural Energy Density, 800 Hz
Summary: High-Frequency EFEA

- EFEA provides computationally efficient method for high-frequency analysis
  - Model is generated from same CAD data as for conventional FEM
  - Plot of energy vs. frequency: 5 minutes on Sun workstation

- EFEA makes high-frequency analysis accessible to engineers, including large community of FEA users
Conclusions

- New, efficient modeling techniques have been developed for vehicle NVH

- Models have been integrated to predict
  - Vehicle dynamics
  - Structural vibration
  - Radiated noise
  - Acoustic and seismic signatures

- Low- to mid- to high-frequency analyses can be performed using a single FEA-based code

- Analysis tools provide new capabilities for a flexible, distributed design environment
Ongoing and Future Work

- Further development of modeling techniques and associated computer codes
- Implementation in design studies
  - Optimization
  - Target cascading
- Application to hybrid vehicles
- System integration over the internet
  - Different computing platforms
  - Different locations