Noise, Vibration, and Harshness (NVH) Analysis of a Full Vehicle Model

Summary

This technology brief illustrates typical mode-based noise, vibration, and harshness (NVH) analyses of a full automobile model using the Abaqus product suite. Abaqus/AMS, the automatic multi-level substructuring eigensolver, is used to compute the eigensolution. A steady-state dynamic analysis is then performed in Abaqus/Standard. The significant performance benefit of using Abaqus/AMS and the SIM-based linear dynamics architecture will be demonstrated for uncoupled structural and coupled structural-acoustic analyses.

Background

The computational analysis of automotive noise, vibration, and harshness (NVH) performance is most often done with mode-based finite element procedures. The accuracy of such analyses increases if the associated frequency range is increased to cover a larger fraction of the audible spectrum. However, the increased accuracy comes at the expense of model size; mesh refinement must increase to accurately capture higher frequency modes.

As model size increases, more efficient numerical techniques are needed to keep analysis times reasonable. The Abaqus automatic multi-level substructuring (AMS) eigensolver was introduced in Version 6.6 to help meet this requirement.

With the introduction in Version 6.7 of a new architecture called SIM, the performance of the mode-based linear dynamics procedures in Abaqus was improved. The SIM architecture also extends the capability for including dissipative effects, allowing for the use of structural and material viscous damping in steady-state dynamic (SSD) analyses.

The purpose of this Technology Brief is to demonstrate how typical NVH analyses of a full vehicle can benefit from using Abaqus/AMS and the SIM-based SSD analysis procedure.

Finite Element Analysis Approach

A full model of a passenger car, shown in Figure 1, is used for the present analyses. Two SSD simulations will be considered – an uncoupled analysis of the structure only, and a coupled analysis that includes the air in the vehicle.

A mode-based SSD analysis in Abaqus consists of two steps: an eigensolution extraction, followed by a frequency response calculation. For the present analyses,
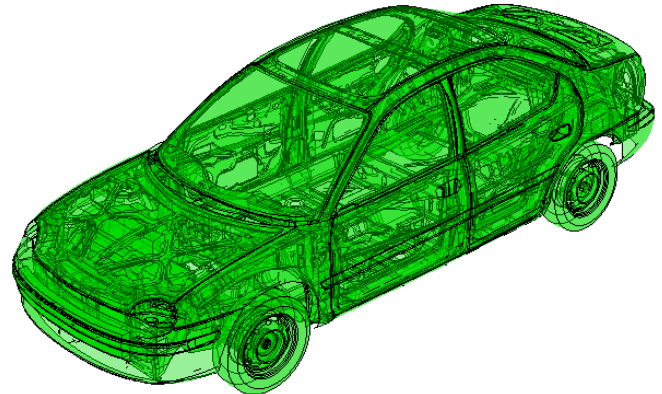
Key Abaqus Features and Benefits

- Automatic multi-level substructuring eigensolver add-on capability for Abaqus/Standard

- SIM architecture for high performance mode-based linear dynamics and structural acoustics simulations

- Material viscous and structural damping effects for SIM-based steady-state dynamic analysis procedures

the upper bound of the frequency extraction range is chosen as 450 Hz, and the frequency response solutions are computed up to 300 Hz.

In both analyses, the rolling motion of the vehicle is simulated with concentrated loads applied to the pivot points on the knuckles of the front wheels; these are denoted as 'Drive Points' in Figure 1. Structural damping is applied to all materials and the vehicle is constrained at the bottom of each tire.

Uncoupled structural analysis

The uncoupled structural model has 271,872 elements and 1,703,161 active degrees of freedom. The AMS eigensolver approximates 2,166 eigenmodes below the global cutoff frequency of 450 Hz. As a comparison, the Lanczos eigensolver computes 2,199 eigenmodes. The AMS and Lanczos eigensolvers use different theoretical approaches to determining the eigensolution, and can thus find different numbers of eigenvalues in a certain frequency range.
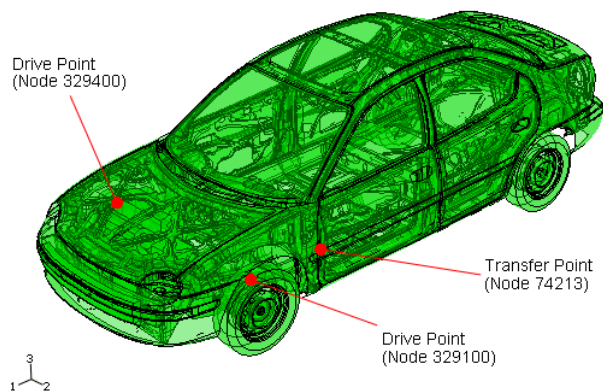
Figure 1: Full vehicle model

The relative errors of the natural frequencies computed by the AMS eigensolver with respect to those computed by the Lanczos eigensolver are shown in Figure 2. Below the global cutoff frequency of 450 Hz, the relative errors are less than 1.15%. Below 300 Hz, the range of interest for the frequency response analysis, the error is less than 0.45%. This indicates that the resonance peaks in the frequency response functions determined with the AMS eigensolution will be accurate. A representative displacement magnitude contour plot is shown in Figure 3.

To compensate for the truncation errors introduced by limiting the number of eigenfrequencies in the solution, residual modes can be included in the frequency response analysis. A residual mode is representative of the static response of the structure when it is subjected to a unit load that corresponds to the actual load used in the SSD analysis.

The frequency response functions are calculated from 1 Hz to 300 Hz at 1 Hz increments. The accuracy of the solution computed by the SIM-based SSD analysis
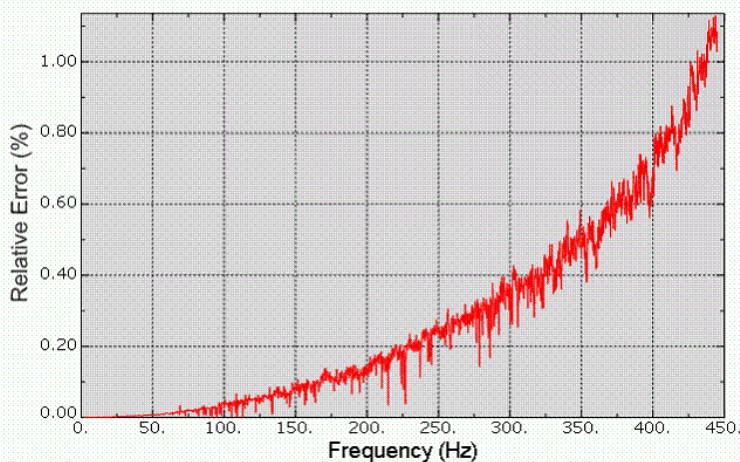

Figure 2: Relative error in natural frequencies obtained by Abaqus/AMS with respect to those obtained by the Lanczos eigensolver.
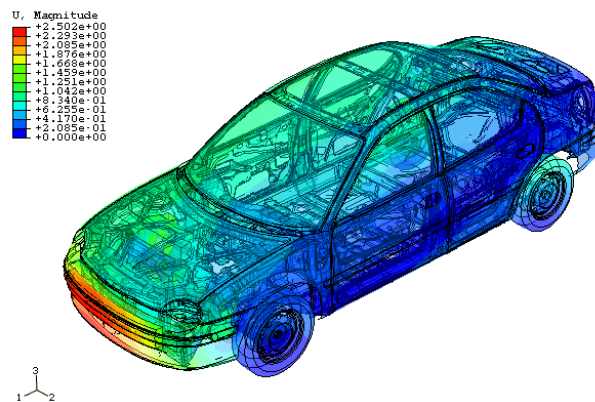

Figure 3: The 10th structural eigenmode at 6.6 Hz

procedure is evaluated qualitatively by comparing it with that computed by the direct-solution SSD procedure. Note that the direct-solution SSD procedure calculates response directly in terms of the physical degrees of freedom of the model. The solutions are compared at two separate output locations: the driver's side drive point, and the transfer point (Figure 1).

Coupled structural-acoustic analysis
A coupled structural-acoustic analysis can be performed by discretizing the air space inside the vehicle and combining the mesh with that of the structural model. The air volume for the vehicle interior is shown in Figure 4.

It is not necessary for the structural and acoustic regions to share nodes. The two regions are coupled by using surface-based tie constraints to join the structural and acoustic meshes. The acoustic portion of the model uses 843,752 tetrahedral acoustic elements. The total number of active degrees of freedom in the coupled structural-acoustic model is approximately 2.3 million.

The eigenmodes of the acoustic region can be computed separately from the structure and included in the modal subspace for the SSD analysis.
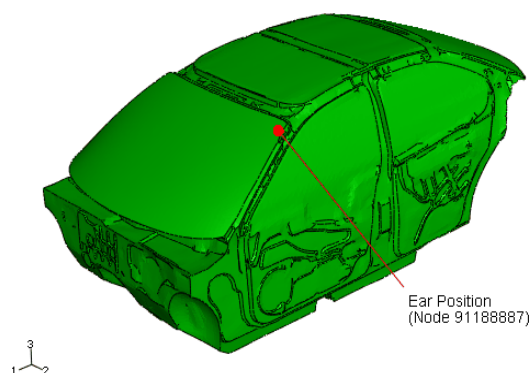

Figure 4: The air volume inside the vehicle.

This is because the coupling between the air and structure is relatively weak. For this structural-acoustic model, 50 acoustic eigenmodes are calculated below the 450 Hz cutoff frequency. A representative acoustic pressure distribution is shown in Figure 5.

To assess the noise level in the vehicle, the acoustic pressure is monitored near the vicinity of the driver's ear (Figure 4). As with the structural analysis, the accuracy of the acoustic response (acoustic pressure) computed by the SIM-based SSD procedure is evaluated by comparing it with results computed by the direct-solution SSD procedure.
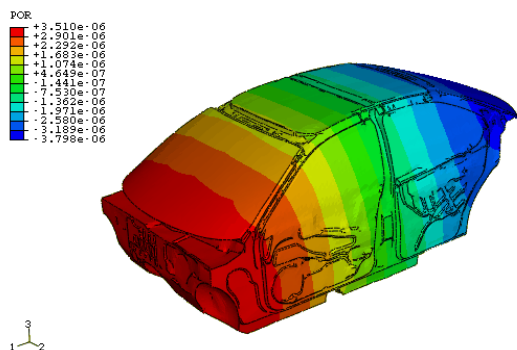

Figure 5: Air pressure distribution for the second acoustic eigenmode at 79.6 Hz.

Results and Discussion

Structural analysis
Figure 6 shows point inertance results at the driver's side drive point (Figure 1), where inertance refers to the ratio of acceleration output over force input. Four curves are shown:

SSD AMS: SIM-based SSD analysis using the AMS eigensolution

SSD AMS RES: SIM-based SSD analysis using the AMS eigensolution and residual modes

SSD LNZ: SIM-based SSD analysis using the Lanczos eigensolution

SSD DIRECT: direct-solution SSD analysis

The results are almost visually indistinguishable for low frequencies. Taking the direct-solution SSD results as the reference, curve **SSD AMS RES** demonstrates how the inclusion of residual modes in the modal subspace can improve accuracy and compensate for modal truncation errors.

Figure 7 shows the transfer point inertance results where the transfer point is located at the bottom of the driver's seat (Figure 1). Four curves are again shown, and throughout the entire frequency range of interest, the frequency response functions of the SIM-based SSD analyses are almost indistinguishable from those of the direct-solution SSD analysis.

The overall performance comparison of three uncoupled structural SSD analyses is summarized in Table 1 (the analysis cost for adding the residual modes is negligible). A 2.6 GHz Linux/x86-64 computer was used to perform the three analyses. Note that the SIM-based SSD analysis capabilities are not currently parallelized; however, the direct solution SSD procedure can use multiple CPUs. It is clear that the performance of the SIM-based SSD analysis using the AMS eigensolver greatly exceeds that of the SIM-based SSD analysis using the Lanczos eigensolver and the parallelized direct-solution SSD analysis.

The wallclock time spent for the mode based procedures can be separated into phases: the eigenmode extraction and projection of damping matrices onto the modal subspace, and the SSD solution.

For the Lanczos analysis, computing the eigensolution requires approximately 5 hours and 40 minutes, with the projection of the damping matrices onto the modal subspace consuming the remaining wallclock time for the first phase. Since the damping projection is done in the finite element subspace, which is 1.7 million degrees of freedom in size, and about 2,200 global eigenmodes are used, the expense of projecting damping matrices is dominant with the Lanczos eigensolver. The expense of the damping projection is comparatively minimal when the AMS eigensolver is used.

Coupled structural-acoustic analysis
The SIM-based SSD analysis with the AMS eigensolver for the coupled structural-acoustic simulation requires approximately 2 hours 22 minutes total wallclock time to compute the frequency responses at 300 frequencies. When the direct solution SSD analysis is performed, it requires more than 13 hours to compute responses at only 12 frequencies.

Figure 8 shows the acoustic pressures at the driver's ear position for the frequency range up to 300 Hz. Points labeled **Coupled SSD DIRECT** are the result of the direct-solution SSD analysis procedure, and curve **Coupled SSD AMS** is the result of the SIM-based SSD analysis procedure using the AMS eigensolution. At the 12 selected frequencies, the acoustic pressures computed by the SIM-based SSD analysis procedure are almost identical to the ones computed by the direct-solution SSD analysis procedure.

Conclusion
Typical NVH analyses using the AMS eigensolver and the SIM-based SSD analysis procedure have been shown in this Technology Brief. When compared with direct solution and Lanczos based SSD procedures, the combination of the AMS eigensolver and the SIM linear dynamics architecture provides greatly improved performance for practical industrial simulations.
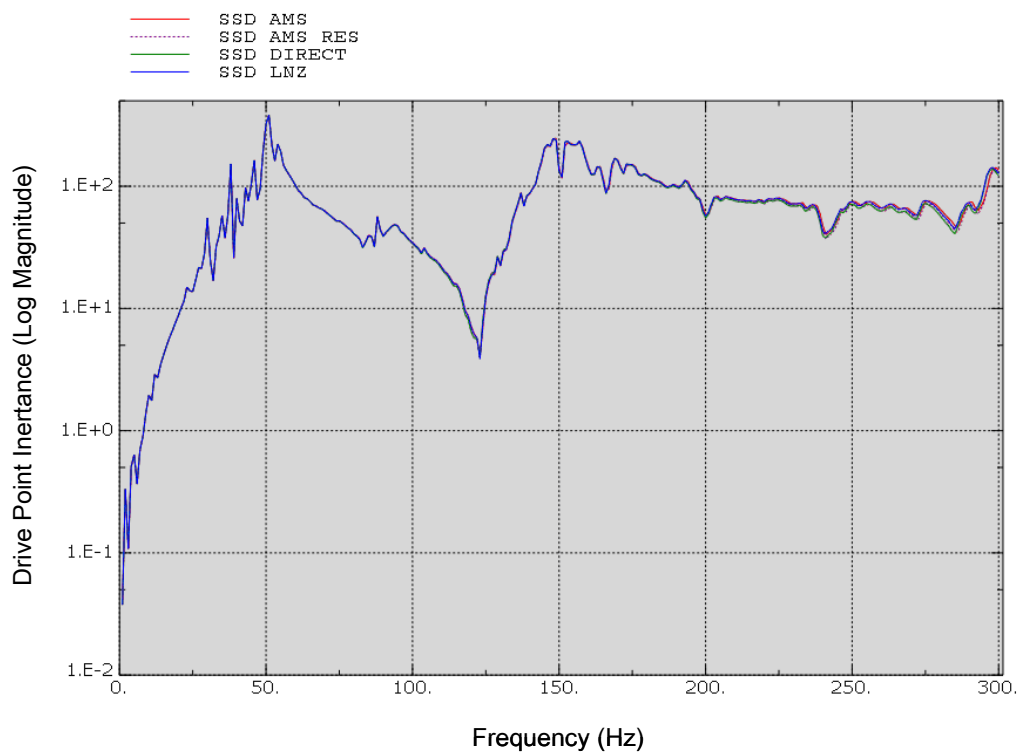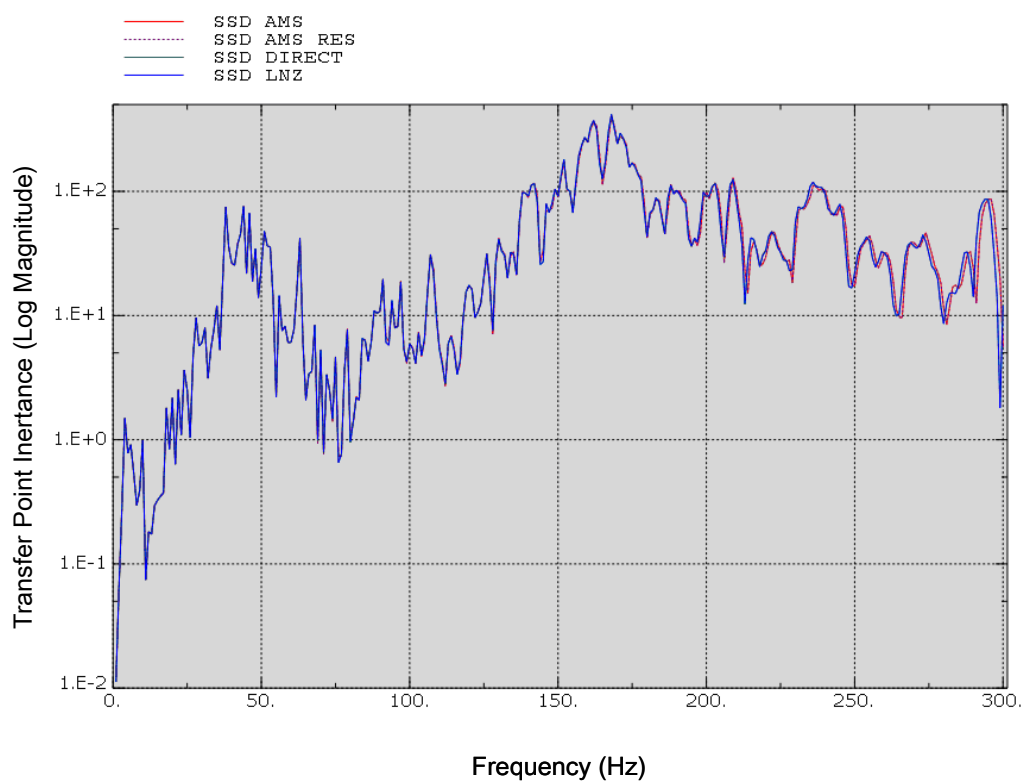
Figure 6: Point inertance at front left drive point.

Figure 7: Transfer inertance at driver seat.

Performance	SSD AMS	SSD Lanczos	SSD Direct[1] 4 CPUs
Total wallclock time	01:01:56	18:47:49	18:24:02
Wallclock time for eigensolver and damping projection	00:34:33	18:17:30	N/A
		05:38:31 for Lanczos only	
Wallclock time for SSD	00:27:23	00:30:19	18:24:02
Required disk space	26.65 GB	35.29 GB	11.74 GB

Note 1: SSD Direct only supports parallel equation solution, not parallelized element operations

Table 1: Overall performance comparison of the Version 6.7-1 SSD analyses for the uncoupled structural model (hh:mm:ss).
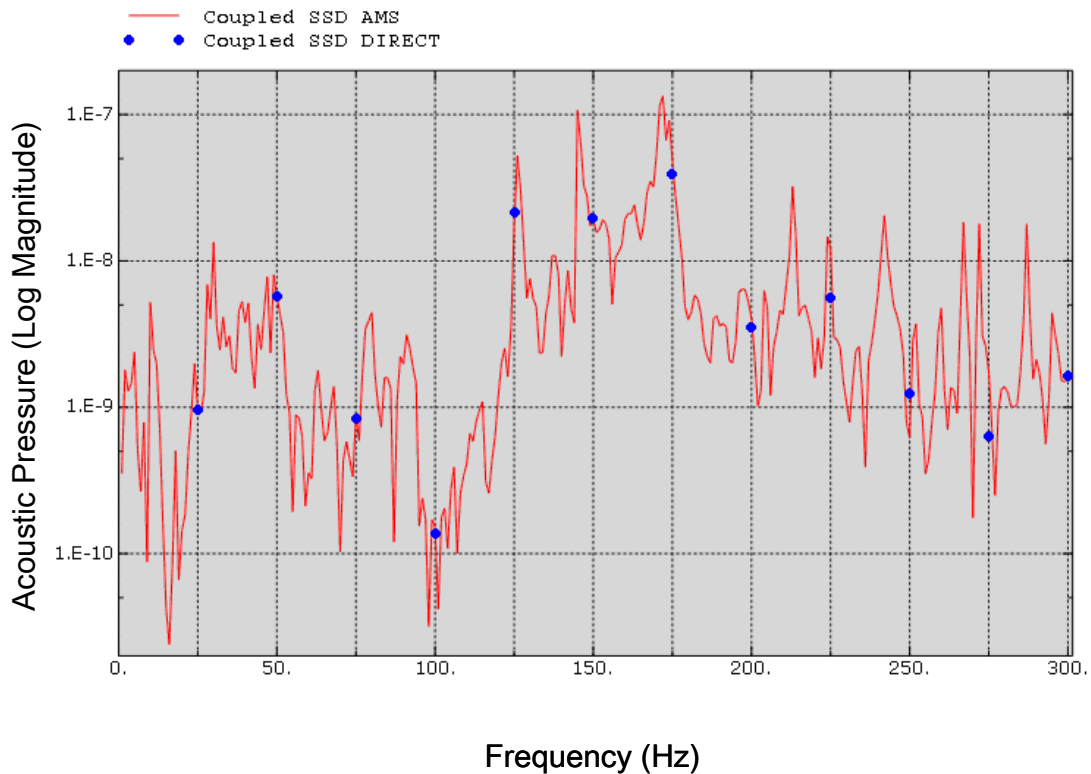
Figure 8: Acoustic pressure at the ear position.

Acknowledgements

References

1. Abaqus Answer ID 3060, "Setting the cut-off frequencies when using the AMS eigensolver."
2. J. K. Bennighof and M. F. Kaplan, M. B. Muller, and M. Kim, "Meeting the NVH Computational Challenge: Automated Multi-level Substructuring," Proceedings of the 18st International Modal Analysis Conference, San Antonio, Texas, February 2000.
3. M. F. Kaplan, "Implementation of Automated Multilevel Substructuring for Frequency Response Analysis of Structures," Ph.D. Dissertation, University of Texas at Austin, Texas, 2001.
4. D. J. Ewins, "Modal Testing: Theory and Practice," Research Studies Press LTD., Hertfordshire, England, 1984.

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, please see the following Abaqus 6.11 documentation references:

- Analysis User's Manual
    - "Using the SIM architecture for modal superposition dynamic analyses" in "Dynamic analysis procedures: overview," Section 6.3.1
    - "Direct-solution steady-state dynamic analysis," Section 6.3.4
    - "Natural frequency extraction," Section 6.3.5
    - "Mode-based steady-state dynamic analysis," Section 6.3.8
    - "Subspace-based steady-state dynamic analysis," Section 6.3.9
    - "Acoustic, shock, and coupled acoustic-structural analysis," Section 6.10.1
- Example Problems Manual
    - "Steady-state dynamic analysis of a vehicle body-in-white model," Section 2.2.6
    - "Coupled acoustic-structural analysis of a pick-up truck," Section 9.1.6

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