

Vehicle NVH Analysis Using EFEA & EBEA Methods

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ABSTRACT

The Energy Finite Element Analysis (EFEA) has been developed for computing the structural vibration and the interior noise level of complex structural-acoustic systems by solving governing differential equations with energy densities as primary variables. Results from EFEA simulations have been compared successfully with test results for Naval, automotive, and aircraft structures. The Energy Boundary Element Analysis (EBEA) has been developed for exterior acoustic computations using the acoustic energy density as primary variable in the formulation. EBEA results have been compared successfully to the test results in the past for predicting the exterior acoustic field around a vehicle structure due to external noise sources. In this paper, the EBEA and EFEA methods are combined for predicting the interior noise levels in a vehicle due to exterior acoustic sources. The EBEA is employed for computing the acoustic field around a vehicle structure due to exterior acoustic noise sources (i.e. tire source, engine source, etc.). The computed exterior acoustic field comprises the excitation for the EFEA analysis. The vehicle structure, the acoustic treatment, and the interior acoustic volumes are represented in the EFEA model. The interior noise level in the vehicle is computed by the EFEA. Predictions of interior noise level (expressed in a noise reduction format) are compared favorably with test results for two separate types of excitation.

INTRODUCTION

In order to perform an airborne noise analysis for an automotive vehicle, it is necessary to compute first the exterior acoustic loading on the vehicle due to the noise sources (i.e. engine, transmission, tires, etc.). Once the exterior acoustic loading has been identified, a structural-acoustic simulation must be performed for computing the vibration induced on the vehicle panels and the noise transmitted in the interior. Capturing correctly the performance of mass barriers, resonant radiation, flanking paths, and acoustic absorption in the structural-acoustic computations is essential for a vehicle's NVH design process. In this paper the EBEA is employed for computing the exterior acoustic loading on the vehicle due to the noise sources and the EFEA is utilized for the structural-acoustic computations.

The EBEA¹⁻⁵ governing integral equation utilizes the acoustic energy and the acoustic intensity as primary variables. Acoustic intensity boundary conditions applied on each element of the EBEA model are used for computing first a distribution of energy sources over the surface of the model. Then, the acoustic energy at any point in the field is evaluated from the EBEA boundary integral equation. In this manner the EBEA can be used for computing the radiated noise when the acoustic intensity is specified on the surface of the radiator^{1,2}. The EBEA can also be used for computing the acoustic field in the vicinity of a vehicle due to external acoustic sources^{3,4}. First, appropriate intensity boundary conditions are computed on the surface of the

model by considering the acoustic intensity originating from the prescribed noise sources and diffraction formulations. Based on the intensity boundary conditions a distribution of energy sources is evaluated over the surface of the boundary element model. The total acoustic field is computed by combining the prescribed exterior noise sources and the distribution of the energy sources on the surface of the boundary element model. In the past the EBEA method was applied for computing the acoustic field around an automotive vehicle and the results were compared favorably to test data^{3,4}.

The EFEA method employs finite elements for solving numerically governing differential equations formulated in terms of the energy densities of the wave types that are present in the structural-acoustic system which is being analyzed⁶⁻¹⁵. The interactions between wave types at connections among different members are captured by comparing appropriate power transfer coefficients. The latter are employed for generating joint matrices associating the various primary variables of the EFEA formulation at the connections between the components of the structural-acoustic system.

In airborne noise simulations the exterior SPL computed by the EBEA comprises the excitation. The EFEA computes the vibration induced on all structural members and the SPL in all acoustic enclosures. In a typical automotive vehicle application the EFEA model is comprised by structural elements, acoustic elements, mass barrier elements, acoustic treatment, and acoustic leakage mechanisms. In this paper the following elements are presented:

1. Description of the EBEA modeling and of the exterior noise simulation.
2. Development of the EFEA model.
3. Discussion of the airborne noise simulation and comparison with measured data.

DEVELOPMENT OF EBEA MODEL AND EXTERIOR NOISE ANALYSIS

The EBEA model is developed using the geometry of the EFEA model and any general purpose pre-processor (i.e. Patran, Hypermesh, etc.). Figure 1 presents the boundary element model utilized in the EBEA simulations from 200Hz to 8,000Hz. The associated computational time is approximately 3 minutes on a Pentium 3.4GHz PC for the entire frequency range. The outer surface of the vehicle is utilized for developing the boundary element model. Two different sources are considered in two separate analyses, namely, acoustic excitation from engine and from tires.

The locations and the strengths of the exterior acoustic sources are specified in each EBEA analysis. Considering the tire source excitation first, four point sources with equal source strengths are placed near the tail edges of front tires and the front edges of the rear tires, respectively. In consistency with the measurement setup, the computation of the strengths of the acoustic sources is explained next.

Considering that there is a single equivalent virtual source which can simulate the contributions from all tires sources, the SPL of this virtual source is set equal to 0 dB at 50mm away from the source:

$$\text{SPL} = 10 \cdot \log \left(\frac{\langle p^2 \rangle}{4 \times 10^{-10}} \right) = 0 \quad (1)$$

thus the mean square acoustic pressure at this virtual source is: $\langle p^2 \rangle = 4 \times 10^{-10} \text{ N}^2/\text{m}^4$. In the EBEA simulation, four actual sources are defined as equivalent with the virtual source, therefore the mean square acoustic pressure for each one of the four actual sources is:

$$\langle p_i^2 \rangle = \frac{\langle p^2 \rangle}{4} = 1 \times 10^{-10} \text{ N}^2/\text{m}^4, i = 1, 2, 3, 4. \quad (2)$$

The relationship between the mean square acoustic pressure at r distance away from the source and the strength σ of source used in EBEA formulation can be expressed by³

$$\langle p_i^2 \rangle_r = \sigma \left(\frac{\rho_0^2 c_0^2}{64\pi^2 r^4} + \frac{f^2 \rho_0^2}{8r^2} \right), \quad (3)$$

where ρ_0 and c_0 are the air density and the speed of sound in air, respectively, r is the distance from the source to the measured location, and f is the frequency (Hz). Finally, the source strength is determined as:

$$\sigma_i = \frac{\langle p_i^2 \rangle_r}{\frac{\rho_0^2 c_0^2}{64\pi^2 r^4} + \frac{f^2 \rho_0^2}{8r^2}}. \quad (4)$$

Equations (1) – (4) are used for defining the strengths of the acoustic sources in the EBEA analysis based on the requirement of 0dB SPL at 50mm away from the equivalent virtual source.

The acoustic sources which represent the engine noise are defined in a similar manner. In this case the SPL at 1 meter distance ($r=1\text{m}$) from the virtual source in the free field is considered equal to 0 dB. Based on experience from the measurements, the directivity factor Q is set equal to 4 for this source, resulting in:

$$\text{SPL}_r = 10 \cdot \log \left(\frac{W}{W_{\text{ref}}} \cdot \frac{Q}{4\pi r^2} \right) \Rightarrow \text{SPL}_{r=1} = 0 \quad (5)$$

$$\Rightarrow W = 3.14 \times 10^{-12} \text{ Watts}$$

In the current EBEA analysis, two nondirectional point sources are used to represent the virtual source, therefore, the sound power for each of these two sources is set equal to $W_i = 1.57 \times 10^{-12} \text{ Watts}$. The relationship between the sound power and the strength σ of each source used in EBEA simulation is:

$$W_i = \sigma_i \frac{\pi \rho_0 f^2}{2c_0} \quad (6)$$

Finally, the source strength is determined:

$$\sigma_i = W_i \frac{2c_0}{\pi \rho_0 f^2} \quad (7)$$

Figures 2 and 3 present representative results for the exterior acoustic loading at 4,000Hz on the vehicle from engine source and from tire sources excitations, respectively.

DEVELOPMENT OF EFEA MODEL

An EFEA model can be developed from the same CAD data which are employed for developing a conventional finite element model (Figure 4). The EFEA model is comprised by both structural elements and acoustic elements. The latter represent all the acoustic cavities which are encountered in the vehicle (i.e. interior passenger compartment, space between door panels, space between dash panel and instrument panel, etc.). Multiple transmission paths contribute to the interior noise levels, namely, non-resonant transmission through trimmed panels, resonant radiation from vibrating components, and flanking paths through gaskets and holes. All these transmission paths are captured by the EFEA model. Additionally, the interior trim components (i.e. carpet, headliners, and side trim) are key contributors to the acoustic performance and they are taken into account when creating the EFEA model for the vehicle.

The acoustic absorptions from the floor carpet, headliner, and side trim are specified over the outer surface of the acoustic cavities. Mass barriers are applied on panels (i.e. dash, floor, door, roof, lift gate, etc.). Mass barrier treatment affects the acoustic performance of panels through modifications in the non-resonant paths. Leakage effects are also defined as appropriate for panels which separate two adjacent acoustic cavities. The EFEA computational time for analyzing the entire frequency range of interest (200Hz – 8,000Hz) on a Pentium 3.4GHz PC is approximately 45 minutes.

The main benefits offered by the EFEA method for automotive airborne NVH simulations are:

1. The EFEA model is created using the same geometry and the same pre-processors (i.e. PATRAN, Hypermesh, etc.) that are utilized for creating conventional finite element models. The process of creating an EFEA model is the same with the one followed for generating a conventional finite element model. Thus, the entire modeling NVH CAE process is streamlined.
2. The acoustic treatment is applied on the actual surface which is in contact with the acoustic medium and where the acoustic treatment actually resides in the physical system.
3. The structural damping and the mass barrier properties can vary from element to element if desired, thus allowing for higher design fidelity of the acoustic treatment.
4. The spatial variation in the results for the structural vibration and for the interior SPL is captured by the EFEA solution.

COMPARISON BETWEEN TEST DATA AND EBEA/EFEA RESULTS

The Noise Reduction (NR) (i.e. the difference in the SPL between the source and the field point of interest) is evaluated for the driver's location. By associating 0dB SPL with each type of acoustic excitation the SPL computed for the driver's location provides directly the NR value. Figures 5 and 6 present results for the NR due to acoustic excitation originating from the engine and from the tires respectively. Results from test and from the EBEA/EFEA simulations are presented in both Figures. Good agreement is observed between both sets of results and for both acoustic sources.

Representative results for the interior SPL due to the two different sources are presented in Figures 7 and 8 for the 4,000Hz frequency. The distribution for the interior