

Guidelines for Using Fast Multipole BEM to Calculate Automotive Exterior Acoustic Loads in SEA Models

Sebastian Müller, Vincent Cotroni and Terence Connelly
ESI US R&D

Copyright © 2009 SAE International

ABSTRACT

Automotive interior noise at mid and high frequencies is typically dominated by the airborne noise from acoustic sources that are spatially distributed around a vehicle. Each source is typically spatially compact (for example, a tire contact patch) but the source radiates sound that then propagates across the entire exterior surface of the vehicle. To characterize a source it is therefore necessary to know both the sound pressure level in the vicinity of the source and also the way in which sound from the source diffracts around the vehicle. The former depends on the details of the source, the latter typically depends on the overall vehicle geometry. When creating Statistical Energy Analysis (SEA) models of interior noise, the diffraction of airborne loads around a vehicle is often measured experimentally. Since SEA deals with averaged quantities, it is typically only necessary to obtain an approximate estimate of the space and frequency averaged sound pressure level across various surface regions of the vehicle (rather than a very detailed narrowband prediction of the diffraction).

This paper provides a numerical investigation of the diffraction of typical acoustic sources around a vehicle using the Fast Multipole Boundary Element Method (FMM BEM). In particular, the paper investigates the sensitivity of the space and frequency averaged diffracted field to various modeling details (for example, geometric detail, mesh density/quality, surface impedance, frequency resolution etc.). The objective of the study is to investigate how much "detail" is needed in an FMM BEM model in order to get accurate predictions of the exterior acoustic loads for use in Statistical Energy Analysis (SEA) models. Significant reductions in computational expense can be obtained by matching the

level of detail in the FMM BEM model to the level of detail required in the input results for an SEA model (and therefore avoiding "over computing" results that are subsequently frequency and space averaged).

INTRODUCTION

SEA is a standard method for the prediction of interior noise in vehicles [1,2]. The analysis is used to define acoustic design targets for various areas of the car body structure, and to define the sound package to meet those targets. The accuracy of the SEA prediction depends on the accuracy of the applied exterior loads. Typically, these loads are expressed as space and frequency averaged pressure levels over specified surface regions (i.e. the sound pressure levels across the SEA subsystems used to model the roof, windows, windshield, etc.).

One way to obtain these exterior sound pressure levels is to use experimental measurements. Obtaining the exterior loads via measurements requires expensive and time consuming testing. If the body structure is completely new, the opportunity to measure the exterior sound field is not possible until hardware is available. Alternatively, semi-empirical formulas may be used [2], however, these can sometimes be approximate and do not allow for the inclusion of additional geometric details in the prediction of the exterior loads. An alternative approach is therefore to try to predict the diffraction around a vehicle using the Boundary Element Method (BEM).

For conventional BEM, the memory usage scales as $O(N^2)$ and CPU time scales between $O(N^2)$ to $O(N^3)$, N being the number of unknowns. A conventional BEM model is therefore limited to fairly low frequencies for full

vehicles: assuming a maximum number of nodes of the order of $N = 10^4$ nodes, and assuming 6 elements per acoustic wavelength, the frequency limit is around 600 Hz for a midsize vehicle.

When combined with the Fast Multipole Method (FMM) [5], a BEM model can be extended to address full vehicle problems over the frequency range typically used for airborne SEA models (400-1250 Hz). With FMM, the BEM memory usage scales as only $O(N)$ and the CPU time as $O(N \times \log(N))$; this represents a significant improvement over standard BEM. The computational advantages arise from the use of a "Multipole" approximation for the interaction of "distant points", as well as from the "Iterative multilevel solution" for the system of equations. The use of FMM allows the solution of BEM models with several million nodes, which is not possible with standard BEM. In this study the commercial software package VA One [4] was used. This software includes an FMM solver based on an iterative flexible generalized minimal residual method (fGMRES). At each iteration a preconditioner to the fGMRES is computed using a low accuracy FMM and an unpreconditioned GMRES [5,6]. This results in fast convergence properties over a broad range of wavenumbers. For exterior problems, the Burton-Miller formulation is used to avoid irregular frequencies (i.e. frequencies where the BEM solution is not unique).

The aim of this study is to investigate the use of Fast Multiple BEM to predict the exterior acoustic loads for use in an automotive SEA model. The study investigates the sensitivity of the diffracted sound pressure level to (i) geometrical details, (ii) mesh density, (iii) mesh quality, (iv) surface impedance, (v) details of the source description (vi) frequency resolution and (vii) solver options.

SUMMARY OF PROCESS

This section summarizes the process used to: (i) create a BEM model of the diffraction of an acoustic source by a car body, and (ii) postprocess the output of the FMM model to define the loads in an airborne SEA model.

BEM MODEL SET UP

Creating BEM Mesh – In order to create an FMM BEM model it is first necessary to create a water-tight surface mesh of the exterior of the vehicle. The mesh can be created from an existing CAD, FE or SEA model. By making use of a shrink-wrap algorithm [4] it is possible to quickly create a watertight mesh from the initial geometry. Mesh coarsening/refining algorithms can then be used to adjust the mesh density and the level of detail in the mesh. When creating BEM meshes, it is typically good modeling practice to ensure that: (i) a sufficient number of elements are used per propagating wavelength and (ii) to ensure that nearby surfaces are separated by at least 2 or 3 element lengths [7]. For the current application it is also useful to split the surface elements into a number of regions over which the space

average sound pressure will be computed as a post-processing step (these regions correspond to the SEA subsystems used in a typical SEA model).

Defining Fluid Domain – Having defined the surface of the vehicle, the next step is to connect the surface to a "Boundary Element Fluid" subsystem and to define the "impedance boundary conditions" that the vehicle presents to the fluid. The simplest approach is to assume the structure is completely rigid. However, the various body panels have a finite surface impedance that may influence the diffraction around the vehicle. This surface impedance depends not only on the construction of the body but can also depend on the presence of any trim applied inside the vehicle. One way to estimate the surface impedance is to use a standard airborne SEA model (which contains the major body panels and the sound package). In the following work, a script was developed for extracting the surface impedances (for a particular angle of incidence) from an airborne SEA model of a vehicle. These surface impedances were then used to define locally reacting boundary impedances in the FMM model (later sections discuss the sensitivity of the diffracted field to assumptions about these surface impedances).

The analysis in this paper considers the response of a vehicle in a hemi-anechoic chamber; a rigid infinite plane is therefore added to the BEM fluid to model the chamber floor.

Creating Acoustic Sources – While the sources in an actual vehicle can be very complex, the interior noise typically only depends on the overall sound pressure spectrum in the vicinity of the source and the diffraction of the source around the vehicle. It is therefore often possible to replace a complicated source with an equivalent simplified source that has the same local sound pressure level (and far-field directivity). In the following analysis a monopole is used to model sources that are spatially compact (such as tire or exhaust noise). As will be shown in the paper, the directivity of the source (in addition to the source spectrum) can sometimes have a significant impact on the diffracted pressure field.

Defining Solve Options – Before running the FMM BEM solver, the analysis frequency domain is defined. The FMM solver used in this study is typically accurate for values of kD below 250 (where k is the acoustic wavenumber and D is a characteristic length of the BEM domain). This equates to approximately 40 wavelengths and determines the upper frequency of the analysis. It is also possible to use frequency interpolation of the BEM matrices to save time and memory (this was investigated as part of the current study). The FMM BEM solver used in this analysis is iterative and therefore requires the definition of a convergence tolerance. The convergence tolerance provides a useful way to tradeoff accuracy and speed and the following sections discuss the optimal setting of this parameter when using FMM BEM to define the loads in SEA models.

CALCULATION OF SEA LOADS

The output of the FMM BEM solver run is the pressure response at all nodes on the surface of the vehicle at each frequency of interest. An example of a typical surface pressure distribution around the vehicle is shown in Figure 1a.

The space and frequency surface pressure used in an SEA model is obtained by calculating the RMS pressure across each of the surface regions (or “FE faces”) of interest. The calculation of the space and frequency averaged surface pressure is a standard post-processing operation in the software that was used in this analysis. In the following analysis the pressure response is computed in 1/3rd octave bands. An example of the space and frequency average pressure is shown in Figure 1b.

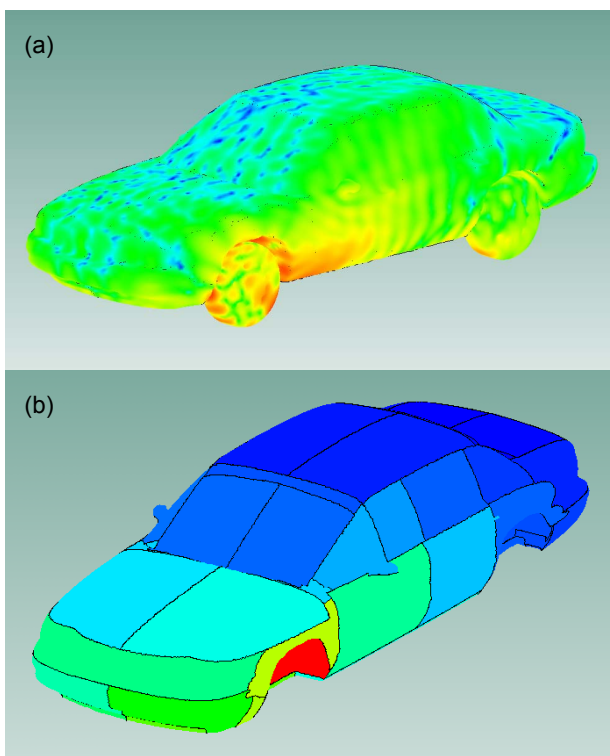


Figure 1. (a) Diffracted sound pressure field at 1337 Hz; monopole next to the driver side front tire. (b) Space and frequency averaged sound pressure level over surfaces corresponding to the exterior SEA subsystems.

ANALYTICAL NUMERICAL STUDY

An initial numerical study was performed to investigate the accuracy of the FMM BEM solver on a simple problem for which analytical solutions are available. Figure 2a shows the diffraction of a plane wave by a 1m diameter rigid sphere at a frequency of 7 kHz. Analytical results for this problem are available in reference [10]. An FMM BEM model was created in which the sphere was represented by approximately 1 million elements and excited by an incident plane wave. The mean error between the analytical results and the FMM BEM results

was found to be less than 0.23 dB (as shown in Figure 2b). This problem took approximately 46 min to solve with a peak memory usage of 1.3 GB (on a 4 CPU 2.2 GHz Win64 machine).

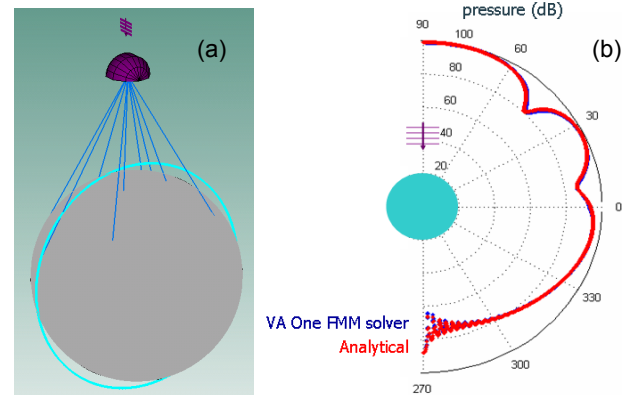


Figure 2. Pressure response around a 1m diameter rigid sphere at 7kHz due to an incident plane wave. Comparison of FMM BEM result against analytical solution.

AUTOMOTIVE NUMERICAL STUDIES

The following sections discuss various numerical studies that were carried out using the FMM BEM model. The objective of this analysis is to determine how much detail is needed in an FMM BEM model in order to get accurate estimates of the exterior loads for use in airborne SEA models. The numerical studies consider the diffraction of a point acoustic source next to the front driver side tire of a sedan. The frequency range of interest is from 400 to 1250 Hz and the SEA loads are computed in the corresponding six 1/3rd octave frequency bands. The results for key subsystems such as the hood, roof, doors, etc. were used to quantify the impact of modeling choices on both the accuracy of the prediction and the computational expense of the solution. The software package VA One was used in this analysis; certain features of the FMM solver in this software may not necessarily be available in all FMM implementations; the conclusions of this study may therefore not be applicable to other FMM implementations.

The following sections describe in detail the investigated modeling options. Unless otherwise specified, the charts show the results for the 1/3rd octave band around 1250 Hz (in most of the cases, the behavior observed was found to be insensitive to the frequency band). The subsystems are sorted according to the pressure response (highest on the left). The CPU time information is always normalized by a reference configuration.

GEOMETRICAL DETAILS

One of the first questions that was addressed in the study was “how detailed does the geometric description of a vehicle need to be in order to get accurate predictions of the diffraction?”. To answer this question, two meshes of the car geometry were created. The